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REDUCTION OF SHIPBOARD 400-HZ POWER REQUIREMENTS. COST AND TECH--ETC(U)
MAY 77 E KAMM, J FOUTZ
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Technical Document 107

REDUCTION OF SHIPBOARD 400-Hz POWER REQUIREMENTS

Cost and Technological Feasibility

Edith Kamm
Jerrold Foutz

16 May 1977

Prepared for
NAVAL SEA SYSTEMS COMMAND
NAVSEA 0331
AND
NAVAL SHIP ENGINEERING CENTER
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NAVAL OCEAN SYSTEMS CENTER
SAN DIEGO, CALIFORNIA 92152

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This document provides the technical background and bibliography for NELC TD 488, Reduction of Shipboard 400-Hz Power Requirements – Executive Overview, by J Foutz and E Kamm, 1 October 1976. It points out the considerable costs and system penalties associated with shipboard frequency changers (MG sets) and explores technological methods of reducing the need for such equipment. It suggests that shipboard electrical equipments and systems be designed to use power in the form generated by the platform's primary electrical power source and that switching mode power supplies might be used as a method of eliminating the need for frequency changers. It explains that whether or not frequency changers are eliminated, the problems –

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of reducing harmonic currents and powering pulse loads will remain. Recommendations include an educational program to make the problems and applicable new technologies known, modification of specifications and standards to require the use of power in the form generated by the platform's primary electrical power sources, and expansion of R&D activities associated with the remaining problems.

OBJECTIVE

Investigate the cost and system penalties associated with shipboard frequency changers and explore technological methods of reducing the need for such equipment.

RESULTS

1. Frequency changers aboard Navy ships have high acquisition, operating, and system costs.

2. Properly applied, switching mode power supplies like those now being used in shipboard electronics for other purposes can be used to eliminate the requirement for frequency changers.

3. The need for shipboard frequency changers could be reduced cost effectively in a time period approximating the average life cycle of an electronic system.

4. Whether or not frequency changers are eliminated, the problems of reducing harmonic currents and powering pulse loads will remain.

RECOMMENDATIONS

1. Inform the Navy technical and management community of the desirability and opportunity of reducing the need for frequency changers.

2. Modify specifications and standards to require equipments and systems to use power in the form generated by the platform primary electrical power sources.

3. Provide technical support to acquisition managers and contractors who are unfamiliar with the switching mode power technology.

4. Expand R&D activities associated with harmonic current suppression and pulse loads.

PREFACE

The objective of this technical document is to provide the technical background and bibliography for NELC TD 488, Reduction of Shipboard 400-Hz Power Requirements – Executive Overview, by J Foutz and E Kamm, 1 October 1976. It has been written as a free-standing document to avoid cross references to TD 488. It therefore includes both the information from TD 488 and additional material needed to more completely document the work.

This is the second phase of the work. The first phase is reported in NELC TN 2828,* Conversion of 400-Hz Shipboard Electronic Equipment to 60-Hz Electrical Power Sources, by J Foutz and E Kamm, 7 November 1974, which completed the NAVSEC OMN portion of the project.

*NELC technical notes are working documents and do not represent an official policy statement of NOSC.

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INTRODUCTION

Except on a few small high-performance ships such as hydrofoils and surface-effect ships, the shipboard prime electrical power for Navy ships is supplied by turbine generators with three-phase, 60-Hz, 450-V ac output. Most shipboard machinery and electronic systems use 60-Hz power, but there are some that require 400-Hz power. For these loads a 60- to 400-Hz frequency changer, usually a motor-generator (MG) set, is used (fig 1). MG sets typically have logistic problems, poor reliability and maintainability, and undesirable load coupling that is attributable to source impedance effects.

To alleviate these major problems, the Navy is conducting a variety of programs that include

Redesigning the MG sets as well as improving them with modification kits

Replacing the MG sets with solid-state frequency changers

Combining frequency changers with other components such as passive and active filters, to give better system performance.

This program investigates the cost and system penalties associated with shipboard frequency changers. The high cost of frequency changers is emphasized to stimulate effective action toward reducing their use in future Navy ships.

This program investigates the possibility of eliminating the need for frequency changers through the use of other technologies and shows that those technologies are available. Particularly significant [illegible] availability of switching regulator technology, a momentous technological advance w[illegible] taken place in recent years in the field of power conversion.

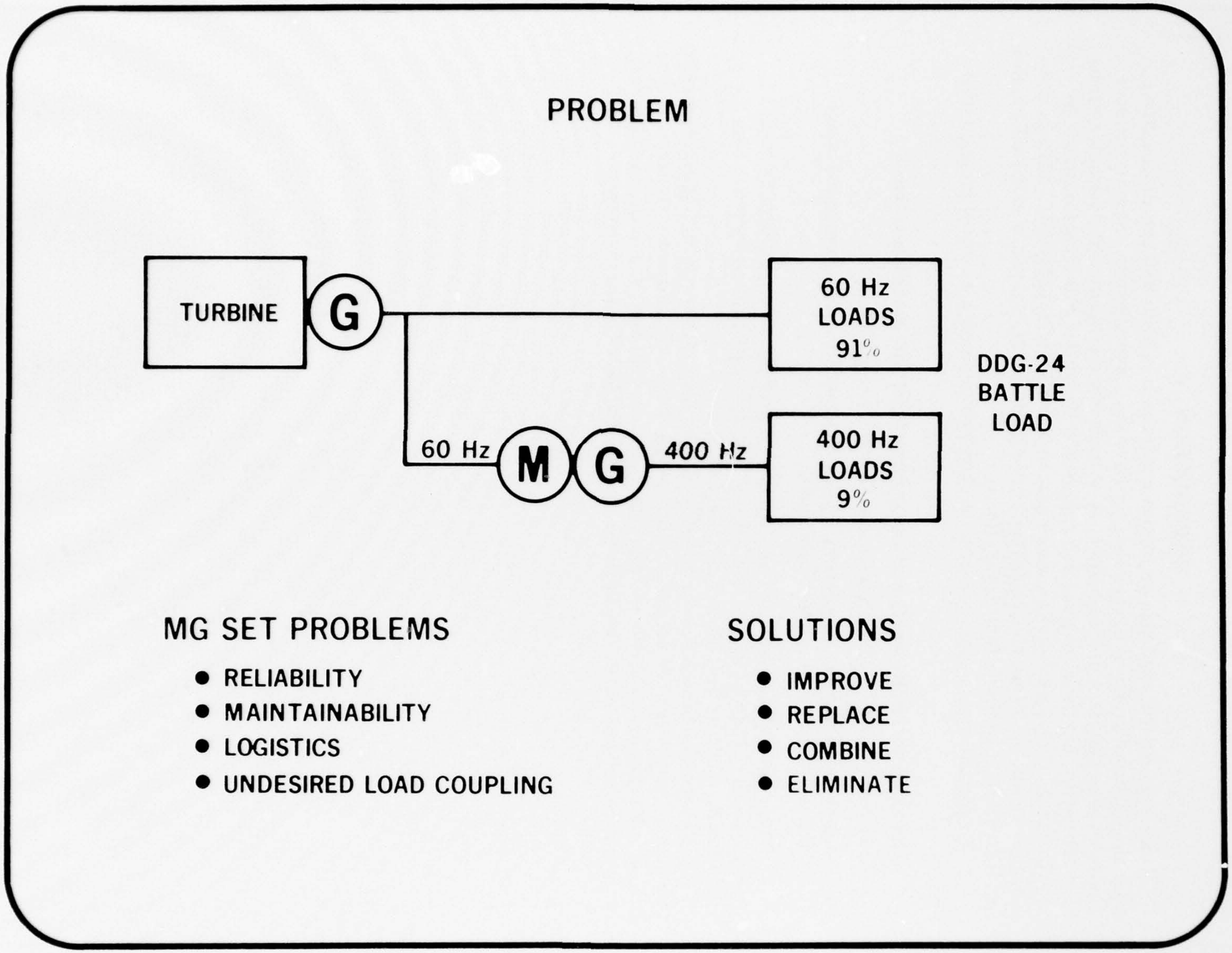
PROBLEM
TURBINE
G
60 Hz
LOADS
91%
DDG-24
BATTLE
LOAD
60 Hz
M
G
400 Hz
400 Hz
LOADS
9%
MG SET PROBLEMS
● RELIABILITY
● MAINTAINABILITY
● LOGISTICS
● UNDESIRED LOAD COUPLING
SOLUTIONS
● IMPROVE
● REPLACE
● COMBINE
● ELIMINATE

Figure 1.

APPROACH

First an overall review was performed of shipboard electrical power system components, including frequency changers, both motor-generator (MG) sets and solid state frequency changers (SSFCs). Then the specific power system of four diverse ships was looked at.

The historical reasons for using 400-Hz power were reevaluated in the light of current technology. Two trends in power electronics were shown to negate the classical size and weight advantages of 400-Hz power over 60-Hz power.

The costs of frequency changers were examined from data obtained for installation, reliability, maintainability, space, weight, fuel, and impedance coupling. Also, specific cost examples from Navy letters and reports were looked at. The annual maintenance and fuel costs were projected for four diverse ship types.

A comprehensive review of the new switching regulator technology was made, because its advent has made it more feasible to reduce the use of shipboard 400-Hz. Various power supply technologies were compared. The advantages of switching regulators were detailed. The Navy's use of switching regulators, the availability of switching regulator technology, and potential problems involving switching regulators were then studied.

Shipboard components other than power conversion circuitry were examined to determine their impact on designing for frequency independence.

Also reviewed were two problems found in both 400-Hz and 60-Hz shipboard power systems – harmonic currents and pulse loads. For harmonic currents, several potential solutions were examined.

DESCRIPTION OF SHIPBOARD ELECTRICAL POWER SYSTEMS

INTRODUCTION

The shipboard electrical power system is first described in general terms. Frequency changers are then described in greater depth. A more detailed description is then given of four ships in different classes: USS DOWNES, USS BERKELEY, USS HALSEY, and USS CONSTELLATION.

GENERAL DESCRIPTION

Primary electrical power on all Navy ships, with few exceptions,* is generated as three-phase 450-V 60-Hz power. Typically, power is generated by redundant ship service turbine driven generators augmented by emergency generators. Each generator is located in a separate watertight compartment. The electrical power is distributed through ship service switch gear groups and emergency switchboards on ungrounded three-wire 450-V feeders. These feeders supply single large auxiliaries, distribution panels, transformers, automatic bus transfer equipment, and 60- to 400-Hz frequency changers. A casualty power system is provided that consists of portable cables, watertight riser and bulkhead terminals to carry the circuit through compartments without impairing the watertight integrity of the vessel, portable casualty switches, and casualty terminals on distribution panels.

Various protection devices such as circuit breakers and overvoltage relays are provided.

*One exception is the PHM (Patrol Hydrofoil Missile) class of ships.

The combined 60-Hz generation and distribution system forms a redundant electrical system capable of providing electrical power even after sustaining considerable damage such as compartment flooding; the shorting of a feeder to the hull; and loss of cabling, generators, switch panels, and transformers. Since ship steering, firefighting, combat capability, and other vital functions depend on electrical power, the availability of electrical power to these functions is vital to the ship. Ship service 60-Hz power provides these vital electrical needs.

The characteristics of shipboard ac power are controlled by an interface standard for shipboard systems: MIL-STD-1399, Section 103 – Electric Power, Alternating Current.[1] The characteristics of the power are controlled at the load distribution panels. The power described so far is defined in the interface standard as three-phase 60-Hz 440-V ac Type I power and is designated in the interface standard as the preferred power. If power with any other characteristics is required, additional equipment must be added to the ship service power system. The least equipment impact occurs if single-phase rather than three-phase power is used – no equipment is added, but care must be taken to maintain line balance, and the harmonic current amplitude distribution may be changed.

The use of 115-V ac power instead of 440-V ac has somewhat greater impact. Three single-phase transformers are then added to the system. Additional distribution and protection circuitry is also required.

Type I power is regulated to ±5 percent. If Type II power, regulated to ±1 percent, is required, line voltage regulators must be added to the system near the distribution point.

The major impact to the power system occurs if a change in frequency from 60 Hz to 400 Hz is required. Some electrical loads, mostly electronics, require 400-Hz power. This power is provided by 60-Hz motors driving 400-Hz generators (MG sets) or by solid-state 400-Hz inverters operating from dc power, which is obtained by rectification of ship's three-phase 60-Hz power. The 400-Hz system has its own distribution system consisting of feeders, control panels, transformers, etc and is provided as ship service power.

Since the 400-Hz power system requires the 60-Hz system for operation, 400-Hz ship service power is always a less reliable source of power than 60-Hz ship service power. As explained in the following section, other characteristics tend to make 400-Hz power even less reliable.

FREQUENCY CHANGERS – 60 Hz TO 400 Hz

Ac power at 400 Hz is provided by frequency changers, usually motor-generator (MG) sets, but solid-state inverters are starting to be used. The characteristics of shipboard 400-Hz power are specified by MIL-STD-1399, Section 103, for Types I, II, and III power, in which Types I and II have the same characteristics as those for 60 Hz and Type III is more closely regulated, with steady-state average voltage and frequency both within 0.5 percent.

MOTOR GENERATOR SETS

There are two military specifications covering 60-Hz to 400-Hz ac motor-generator power supplies for Navy surface ships. MIL-M-19160C[2] specifies general-purpose MGs whose

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[1] Department of the Navy Military Standard MIL-STD-1399, Section 103, Interface Standard for Shipboard Systems, Electric Power, Alternating Current, 1 December 1970

[2] Department of the Navy Military Specification MIL-M-19160C (SHIPS), Motor-Generator, 60 Hertz to 400 Hertz AC, Shipboard Service, 30 September 1970

voltage is regulated to ±0.5 percent. MIL-M-19633B[3] specifies general-purpose and special-purpose MGs whose voltage and frequency are regulated to ±0.5 percent and which require voltage balance regulators. For both specifications, the motor is required to operate from three-phase 440-V ±10 percent, 60-Hz ±5 percent power. The generator for both specifications is required to supply output power with kilowatt (kW) ratings of 5, 10, 15, 30, 60, 100, 200, or 300, as specified; per MIL-M-19160C, generators can also have 0.5-, 1.5-, or 3-kW ratings. The kW rating of an MG set is important because it affects the output impedance of the MG set. The lower the kW rating the higher the output impedance, therefore the greater the possibility of interaction between loads on the same MG set.

MG sets are often used as filters in addition to their main function of changing frequency. The mechanical inertia of the MG set acts as an integrator or low pass filter, both to protect the power source from load transients and to protect the load from power-source transients. An MG set will also isolate load harmonic currents from the source, thereby acting as a harmonic current filter. It is this filtering function of MG sets that results in the dedication of MG sets to specific equipments.

Because the MG set is a single point of failure for a system, redundant MG sets are required to assure the availability of 400-Hz power.

The filtering function and redundancy requirements have resulted in a proliferation of MG sets aboard ships. As many as 17 MG sets are required on the CG class ship having a Terrier missile system. Other ships have as many as 33 MG sets. The ratio of standby (or extra parallel) to loaded MG sets varies from 1:1 to about 1:4 depending on the type and quantity of loaded MG sets used on a ship.

SOLID-STATE FREQUENCY CHANGERS

Solid-state frequency changers perform the frequency changing function with no moving parts and are therefore potentially more reliable and maintainable than motor-generator sets. Since mechanical inertia is eliminated, the solid-state changers can respond faster to changes. However, the inherent filtering function of MG sets (due to mechanical inertia) is not necessarily a characteristic of solid-state frequency changers. Frequency regulation, which is difficult in MG sets, is simple in solid-state frequency changers. For these reasons, solid-state frequency changers are beginning to replace shipboard MG sets and can be expected eventually to totally replace them.

SPRUANCE CLASS FREQUENCY CHANGER. The SPRUANCE (DD 963) Class destroyer uses three 150-kW solid-state frequency changers manufactured by Teledyne-Inet to provide 400-Hz ship service power. This model frequency changer has also been tested on USS TRUXTUN[4,5] and is planned for the yet-to-be-launched patrol frigates. This is the first major use of solid-state frequency changers to replace MG sets aboard US Navy ships.

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[3]Department of the Navy Military Specification MIL-M-19633B (Ships), Motor-Generator, 60 Cycle AC to 400 Cycle AC (Voltage and Frequency Regulated) Shipboard Service, through Amendment-2, 17 January 1972

[4]NAVSEC letter 6732:JK:lml 9620/DLGN-35 FT-4619 Serial 205 to NAVSEC 6155C, Subject: USS TRUXTUN (DLGN 35): Compatibility Checks and Evaluation of 60/400-Hz Solid-State Frequency Changers (SSFC), 9 October 1974

[5]NAVSEC letter 6732:JK:gl 9320, FT-4300, Serial 42 to NAVSEC 6155, Subject: USS TRUXTUN (CGN 35) 400-Hz System Interface Test, 23 March 1976

AEGIS MARK 84 FREQUENCY CHANGER. The AEGIS area defense system requires a 400-Hz power source with outstanding transient response. To meet this requirement, the 300-kW Mark 84 frequency changer is being developed by ALS Electronics for installation aboard the NORTON SOUND. The technology used in the MK 84 is new to the frequency changer field but is well established in other electronic disciplines. The new approach gives superior performance over conventional design approaches.[6]

NAVY STANDARD SOLID-STATE FREQUENCY CHANGERS. The Navy is developing a standard family of solid-state frequency changers from 10 to 250 kW that is expected eventually to replace MG sets and other solid-state frequency changers on Navy ships. The program has been planned to avoid the many problems in reliability, maintenance, logistics, and training that have occurred with previous frequency changers. A three-phase program that will result in prototype units is nearing the end of the second phase.*

SHIP ELECTRICAL POWER SYSTEM DESCRIPTIONS

The electrical power systems of four diverse classes of ships were studied.[7-19] A detailed analysis of the power system was made for a ship selected from each class.

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*Personal Communication from HP Wong, NAVSEC 6158D, to E Kamm on 5 February 1976 at NAVSEC, Hyattsville, MD

[6]Naval Electronics Laboratory Center letter Code 4300 to CDR FE Beck, Naval Ship Engineering Center, Subject: AEGIS MK 84 Frequency Changer Technical Risk Assessment, 15 November 1975

[7]Navy Fleet Material Support Office, Maintenance Material Management (3M) Reports: (a) Report MSO 4790-S2704-F-06, Material History Report, 400-Hz Systems, November 1975; (b) Tracking Report no 2, MSO 47905.3014, FMSO Detection Action Response Technique (DART), 400-Hz MG Sets, August 1975; (c) Report MSO 4790.S2711-01, Logistics High Failure Equips, 14 December 1975

[8]OMMIO Naval Weapons Station, Ordnance Configuration Report, November 1975

[9]NAVSEC Ship Equipment Configuration Accounting System (SECAS) Reports, NAVSHIPS 0967-485-6040: (a) Report 502.1, Item Designation Sequence for DLG 0023, 4 January 1974; – for DDG 15, 14 May 1974; – for DE 1070, 6 December 1974; – for CVA 0064, 16 June 1974. (b) Report 505.1, Field Change Status Report for NA 0064, 16 June 1974; – for DDG 15, 14 March 1975; – for DC 1070, 6 December 1974

[10]Naval Ship Systems Command, NAVSHIPS SIB-CVA 64-3, NS 0205-531-7503, USS CONSTELLATION CVA 64, Ship Information Book, v 3, Power and Lighting Systems, February 1968

[11]Naval Ship Systems Command, NAVSHIPS 0205-636-4300, USS HALSEY DLG 23 Ship Information Book, v 3, Power and Lighting, July 1973

[12]Naval Ship Systems Command, NAVSHIPS SIB-DDG-24-3 NS 0905-011-2031, USS WADDELL DDG 24, Ship Information Book, v 3, Power and Lighting Systems, February 1968

[13]Bureau of Ships, NAVSHIPS SIB-DDG-15-3 NS 0205-702-4300, USS BERKELEY DDG 15, Ship Information Book, v 3, Power and Lighting Systems, July 1963

[14]Naval Ship Systems Command, NAVSHIPS 0905-135-5030, USS DOWNES DE 1070, Ship Information Book, v 3, Power and Lighting Systems, March 1971

[15]Navy Fleet Material Support Office, Maintenance Support Office Department (9311), Equipment Identification Code (EIC) Master Index, Sections I and II, July 1974

[16]Naval Ship Engineering Center Norfolk Division, NAVSEA 0967-6P-034-4010, Index Electronic Equipment Installation Control Drawings, v I, April 1975

[17]BUPERS/NAVPERS Report 10, 794-C, Shipboard Electronic Equipment, 1975

[18]Moore, JE (Editor), Jane's Fighting Ships, Jane's Yearbooks, London, 1975/76

[19]NAVSEA Journal, Fleet Maintenance and Logistic Support News, May 1975

CLASS: KNOX (FF 1052) FRIGATE
SHIP: USS DOWNES (FF 1070)

There are 46 frigates of this class, which is the largest group of frigates built to the same design since World War II. Originally classified as ocean escorts (DE), they were reclassified as frigates (FF) 1 July 1975.

The ship selected from the Knox class is USS DOWNES (FF 1070). The DOWNES was built by Todd Shipyards (Seattle) and commissioned on 28 August 1971. Figure 2 is a simplified one-line drawing of its electrical power systems. The ship's primary power is 60 Hz ac – provided by three ship service 750-kW turbine generators. The 400-Hz system is powered from the 60-Hz system and consists of two 100-kW motor-generators (MGs) and associated switchboards, control panels, and distribution cables. The connected load of the 400-Hz system is about 8 percent of the ship's total connected load.

CLASS: ADAMS (DDG 2) DESTROYER
SHIP: USS BERKELEY (DDG 15)

There are 23 destroyers of this class, built to an improved Forest Sherman design. These destroyers are considered excellent multipurpose ships.

The ship selected from the Adams class is USS BERKELEY (DDG 15). The BERKELEY was built by the New York Shipbuilding Corporation and commissioned 15 December 1962. Figure 3 is a simplified one-line drawing of its electrical power system. The ship's primary power is 60 Hz ac – provided by four 500-kW turbine generators, two power switchgear groups for control and distribution, and two 100-kW emergency generators. The 400-Hz system is powered from the 60-Hz system and consists of two 100-kW MG sets for ship service power and three each 60 kW and 30 kW MG sets for special-purpose 400-Hz requirements. The connected load of the 400-Hz system is about 4 percent of the ship's total connected load.

CLASS: LEAHY (CG 16) CRUISER
SHIP: USS HALSEY (CG 23)

There are nine ships of this class, referred to as "double ended" missile cruisers. They are especially designed to screen fast carrier task forces and were originally classed as guided missile frigates (DLG). They were reclassified as guided missile cruisers (CG) on 1 July 1975.

The ship selected from the Leahy class is USS HALSEY (CG 23). The HALSEY was built by the San Francisco Naval Shipyard and commissioned 30 July 1963. Figure 4 is a simplified one-line drawing of its electrical power system. Primary power is 60 Hz – supplied by four 1500-kW turbine generators with two emergency backup 300-kW gas turbine generators. The 400-Hz system is powered from the 60-Hz system and consists of three 200-kW MG sets for ship service power and eleven 60-kW MG sets for special-purpose 400-Hz requirements such as powering the AN/SPG-55B radar cw illuminator. The connected load of the 400-Hz system is about 13 percent of the ship's total connected load.

CLASS: KITTY HAWK (CV 63) AIRCRAFT CARRIER
SHIP: USS CONSTELLATION (CV 64)

The four ships in this class were built to an improved Forrestal design and are being modified to operate as multipurpose aircraft carriers. The John F Kennedy (CV 67) is

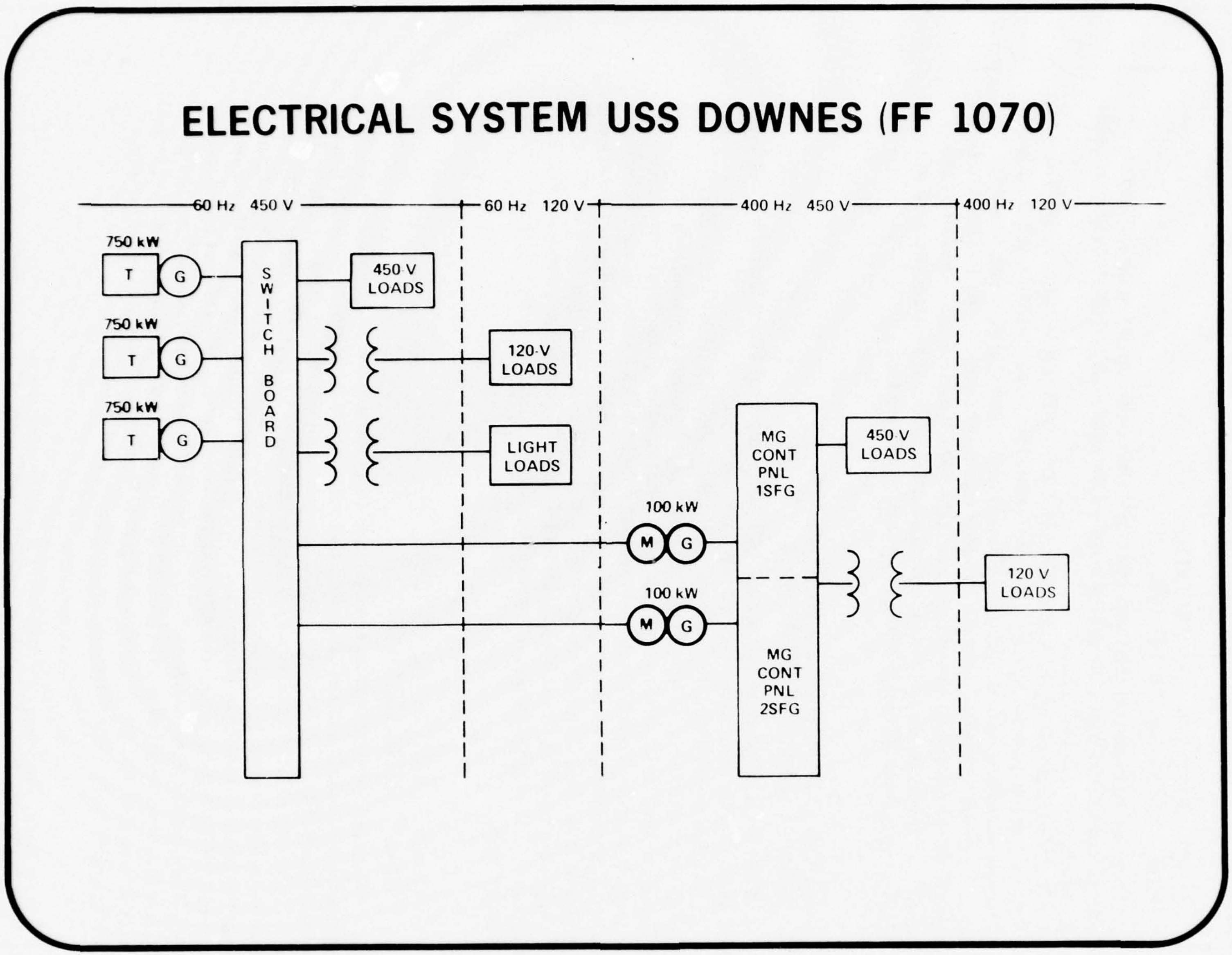
ELECTRICAL SYSTEM USS DOWNES (FF 1070)
60 Hz 450 V
60 Hz 120 V
400 Hz 450 V
400 Hz 120 V
750 kW
T
G
750 kW
T
G
750 kW
T
G
SWITCH BOARD
450 V LOADS
120 V LOADS
LIGHT LOADS
100 kW
M
G
100 kW
M
G
MG CONT PNL 1SFG
MG CONT PNL 2SFG
450 V LOADS
120 V LOADS

Figure 2.

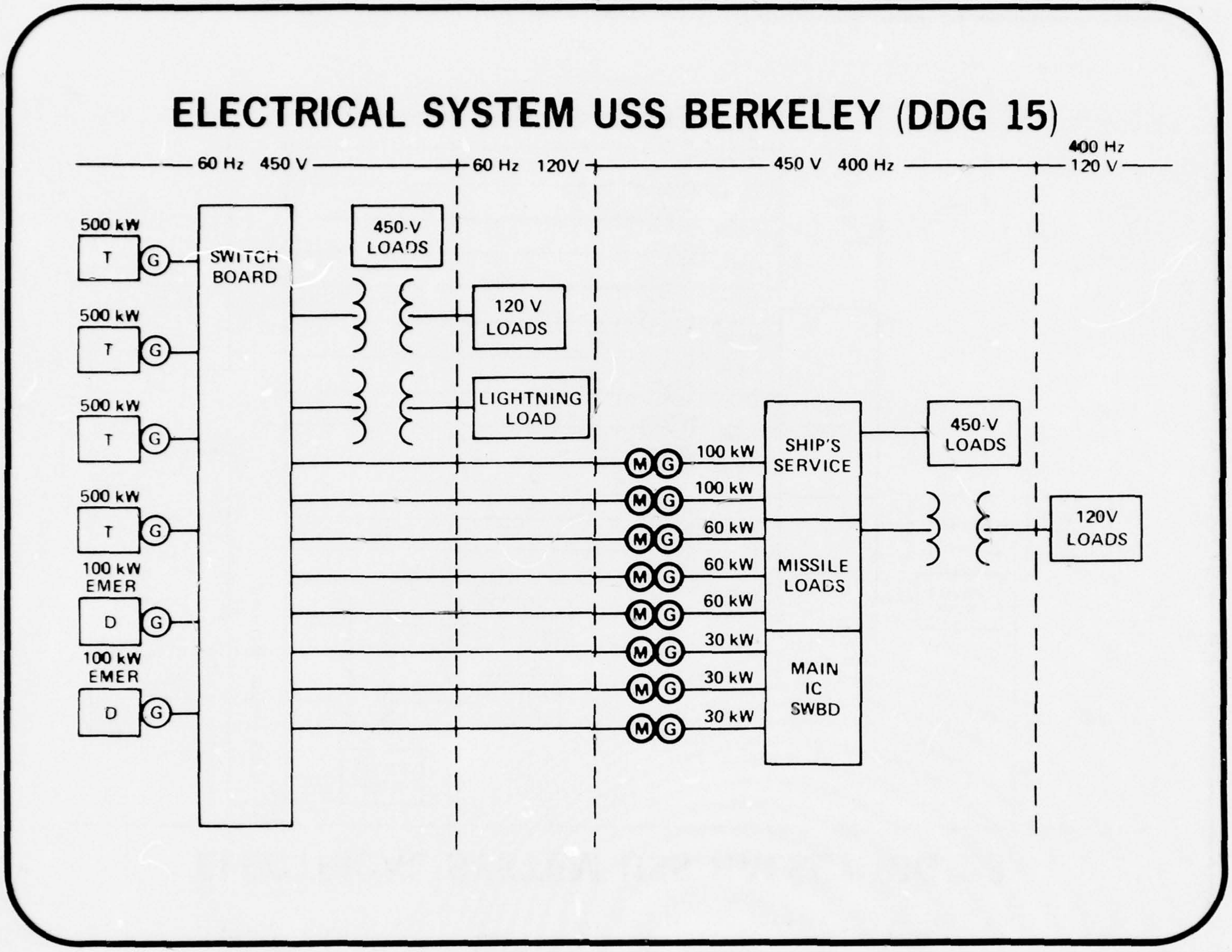
ELECTRICAL SYSTEM USS BERKELEY (DDG 15)
60 Hz 450 V
60 Hz 120V
450 V 400 Hz
400 Hz
120 V
500 kW
T
G
SWITCH BOARD
450-V LOADS
120 V LOADS
LIGHTNING LOAD
100 kW
EMER
D
M
100 kW
60 kW
30 kW
SHIP'S SERVICE
MISSILE LOADS
MAIN IC SWBD
450-V LOADS
120V LOADS

Figure 3.

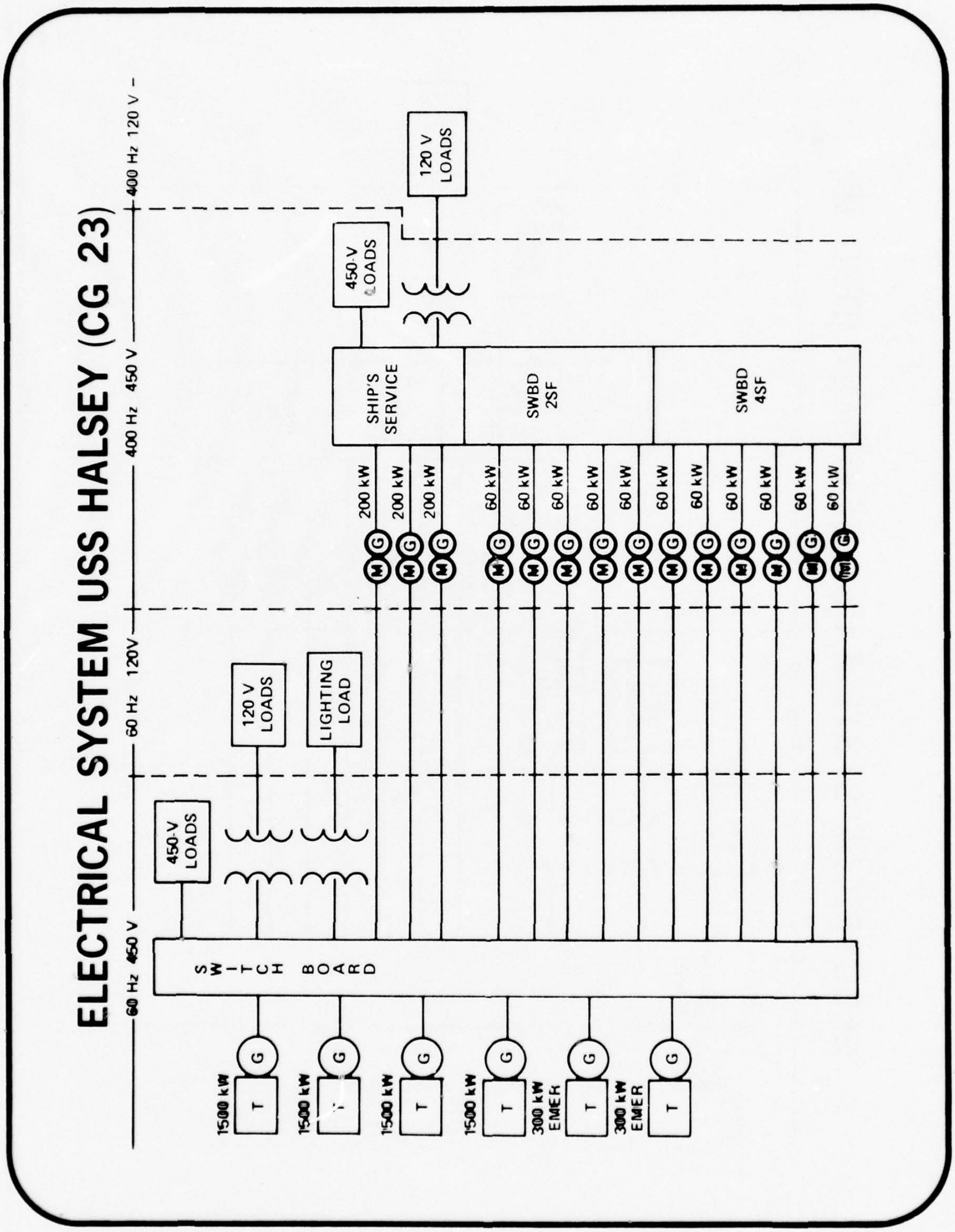
ELECTRICAL SYSTEM USS HALSEY (CG 23)
60 Hz 450 V
60 Hz 120V
400 Hz 450 V
400 Hz 120 V
1500 kW
300 kW EMER
SWITCH BOARD
450-V LOADS
120 V LOADS
LIGHTING LOAD
200 kW
60 kW
SHIP'S SERVICE
SWBD 2SF
SWBD 4SF

Figure 4.

officially a separate one-ship class. All four ships in this class have highly sophisticated electronic equipment, including NTDS.

The ship selected from the Kitty Hawk class is USS CONSTELLATION (CV 64). The CONSTELLATION was built by the New York Shipyard and commissioned 8 October 1961. Figure 5 is a simplified one-line drawing of the electrical power system. Primary power is supplied by eight 60-Hz 1500-kW ship service turbogenerators and, for emergency, three 1000-kW diesel generators. The ship has a 400-Hz prime power system consisting of two 400-Hz 600-kW ship service turbogenerators.* It also has a secondary 400-Hz system powered from the 60-Hz system and consisting of two 100-kW MG sets for ship service power and, for special needs, six 60-kW, three 100-kW, and six 5-kW dedicated MG sets – 15 MG sets in all. The combined installed capacity of these 400-Hz MGs is about 14 percent of the ship's total installed capacity excluding aircraft needs.

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*These two 400-Hz 600-kW turbogenerators have since been replaced by two 300-kW MG sets, and a third 300-kW MG set is to be added.

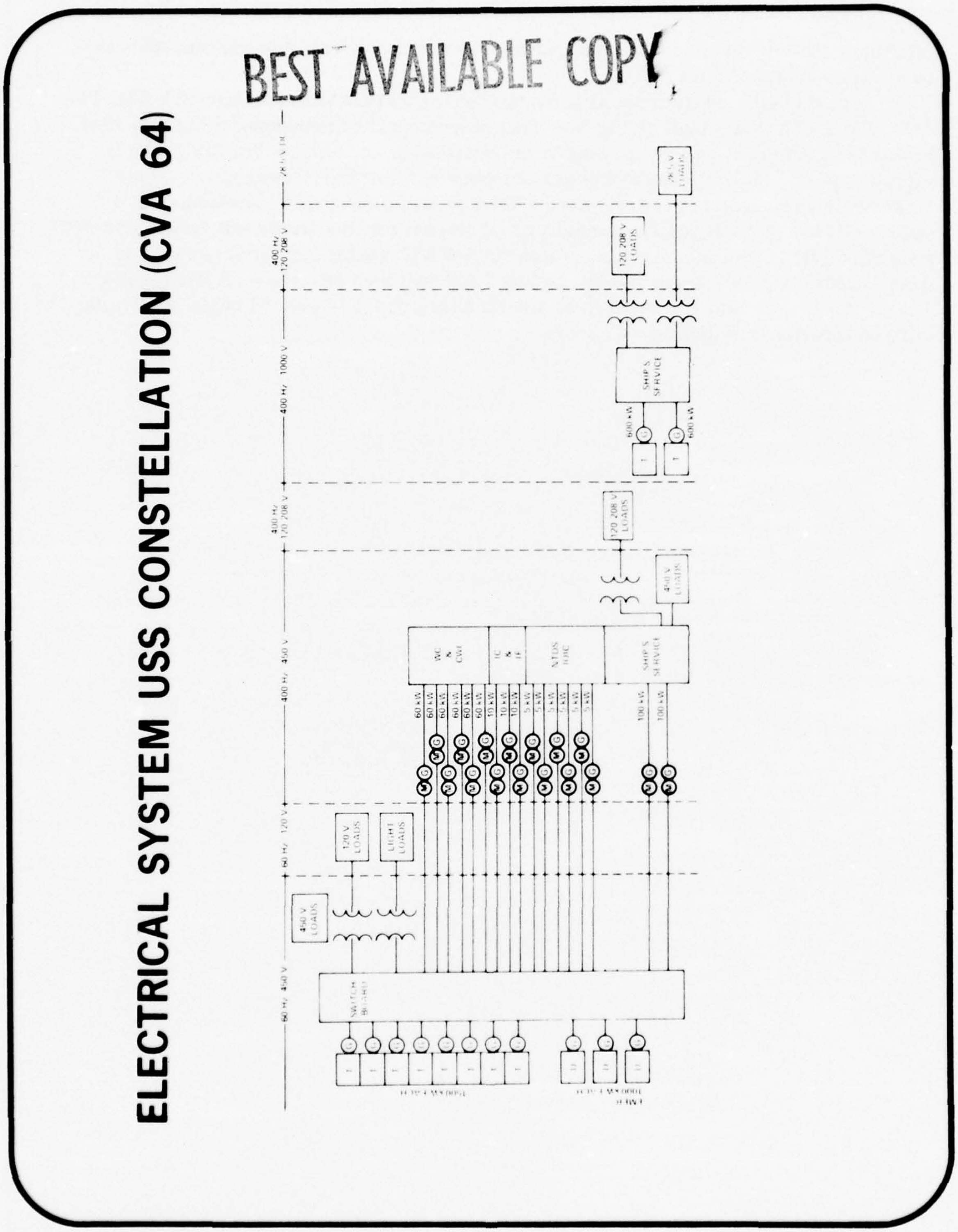
ELECTRICAL SYSTEM USS CONSTELLATION (CVA 64)
60 Hz 450 V
60 Hz 120 V
400 Hz 450 V
400 Hz 120/208 V
400 Hz 1000 V
SWITCH BOARD
450 V LOADS
120 V LOADS
LIGHT LOADS
WC & CWI
IC & FC
NTDS IOIC
SHIP'S SERVICE
120/208 V LOADS
60 kW
10 kW
5 kW
100 kW
600 kW

Figure 5.

HISTORICAL REASONS FOR 400-Hz POWER

For many years the designer of shipboard electronic systems has had the choice of specifying either 60- or 400-Hz input power for specific equipment. During these years the available components and technology allowed him to achieve a smaller and lighter electronic system by specifying 400-Hz input power, because 400-Hz transformers, motors, generators, synchros, and filters are all lighter and smaller than their 60-Hz counterparts. A 400-Hz 50-kW transformer, for example, is 345 pounds (155 kg) lighter than a 60-Hz 50-kW transformer.

The problem with that approach is that the basic shipboard power source is generally a 60-Hz generator. Equipment designed for 400-Hz power input therefore requires a frequency changer between it and the 60-Hz ship service generator. A 60-kW MG set can weigh from 3600 to 5900 pounds (1.6 to 2.7 Mg) depending on its regulation and line-balancing features. For redundancy, a standby MG set often is installed. Thus designing equipment to use 400-Hz electronics so as to "save" 345 pounds (156 kg) actually can add 3600 to 11 800 pounds (1.6 to 5.4 Mg) to the ship's electrical power system.

The realization of this severe weight penalty led to BUSHIPS Instruction 9600.15 of 21 January 1963, which set a policy prescribing the use of 60-Hz power in preference to 400-Hz power. The order of preference was incorporated in superseding specifications MIL-STD-761 followed by MIL-STD-1399, Section 103.

Unfortunately, two factors have worked against the success of the 60-Hz preference policy. First, as explained above, the weight cost of using 400-Hz power seems like a savings instead of a penalty when the tradeoffs are made exclusively at the electronic system level. The overall penalty of using 400-Hz power does not appear until the tradeoffs include the impact on the total ship. Second, the MGs used for frequency changers can serve as filters that smooth out line and load transients and harmonic currents. Although filters are sometimes necessary for operation of electronic systems aboard ship, the penalties involved in using MG sets for filters do not appear until the design tradeoffs are taken above the electronic equipment level.

Figure 6 summarizes the historical reasons for using 400-Hz power.

The following sections discuss transformer and filter weight and system-level versus equipment-level tradeoffs in more detail.

HISTORICAL REASONS FOR 400-Hz POWER

- Availability of choice
- Lighter and smaller magnetics and filters in load
- Ineffective preference policy
- Filtering action of motor generator sets

Figure 6.

TRANSFORMER AND FILTER WEIGHT

Theoretically, the weight of a conventional transformer varies inversely as the 3/4 power of frequency, provided flux density, current density, and other design parameters are held constant.[20] (These parameters are seldom held constant, however, since they affect transformer losses, temperature rise, and regulation.)

Figure 7 compares the weight and volume of the various 60- and 400-Hz transformers used aboard Navy ships. The 400-Hz transformers have about 33 percent of the weight and 40 percent of the volume of 60-Hz transformers with the same kVA rating. Similar weight and size advantages occur for motors, generators, and synchros.

Line filters for 400-Hz systems are also smaller and lighter than those for 60-Hz systems. Theoretically, 60-Hz capacitors are 6.67 times heavier and 60-Hz inductors 4.14 times heavier than their 400-Hz counterparts. (Capacitor weight varies inversely with frequency; inductor weight varies inversely as the 3/4 power of frequency.)

Where size and weight were important, the electronic system designer usually specified 400 Hz over 60 Hz if both were available, merely on the basis of the lighter-weight magnetics and filter. For example, a 50-kW 60-Hz transformer weighs 510 pounds (230 kg), whereas a 50-kW 400-Hz transformer weighs only 165 pounds (74 kg), a savings of 345 pounds (156 kg). The electronics designer took these equipment-level savings as an advantage, failing to consider the impact at the ship level.

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[20] Corey, PD, Analytical Optimization of Magnetics for Static Power Conversion, Supplement to IEEE Transactions on Aerospace, June 1965, vol AS-3, no 2, p 86–89

60-Hz AND 400-Hz TRANSFORMER COMPARISON

REF: MIL-T-15108B (60 Hz)
REF: MIL-T-17221B (400 Hz)

XFMR RATING kVA	XFMR WT 60 Hz LB	XFMR WT 400 Hz LB	WT RATIO	XFMR VOL 60 Hz IN^3	XFMR VOL 400 Hz IN^3	VOL RATIO
1	30	18	0.43	525	335	0.64
3	65	25	0.38	1,020	470	0.46
5	90	30	0.33	1,450	600	0.41
7.5	116	40	0.34	1,910	800	0.42
10	145	50	0.34	2,250	870	0.39
15	206	75	0.36	4,000	1,750	0.44
25	280	105	0.38	5,700	2,150	0.38
37.5	396	140	0.35	7,500	2,750	0.37
50	510	165	0.32	10,025	3,775	0.38
75	695	240	0.35	13,000	4,575	0.35
100	950	310	0.33	17,200	7,100	0.41
		AVG	0.36		AVG	0.42

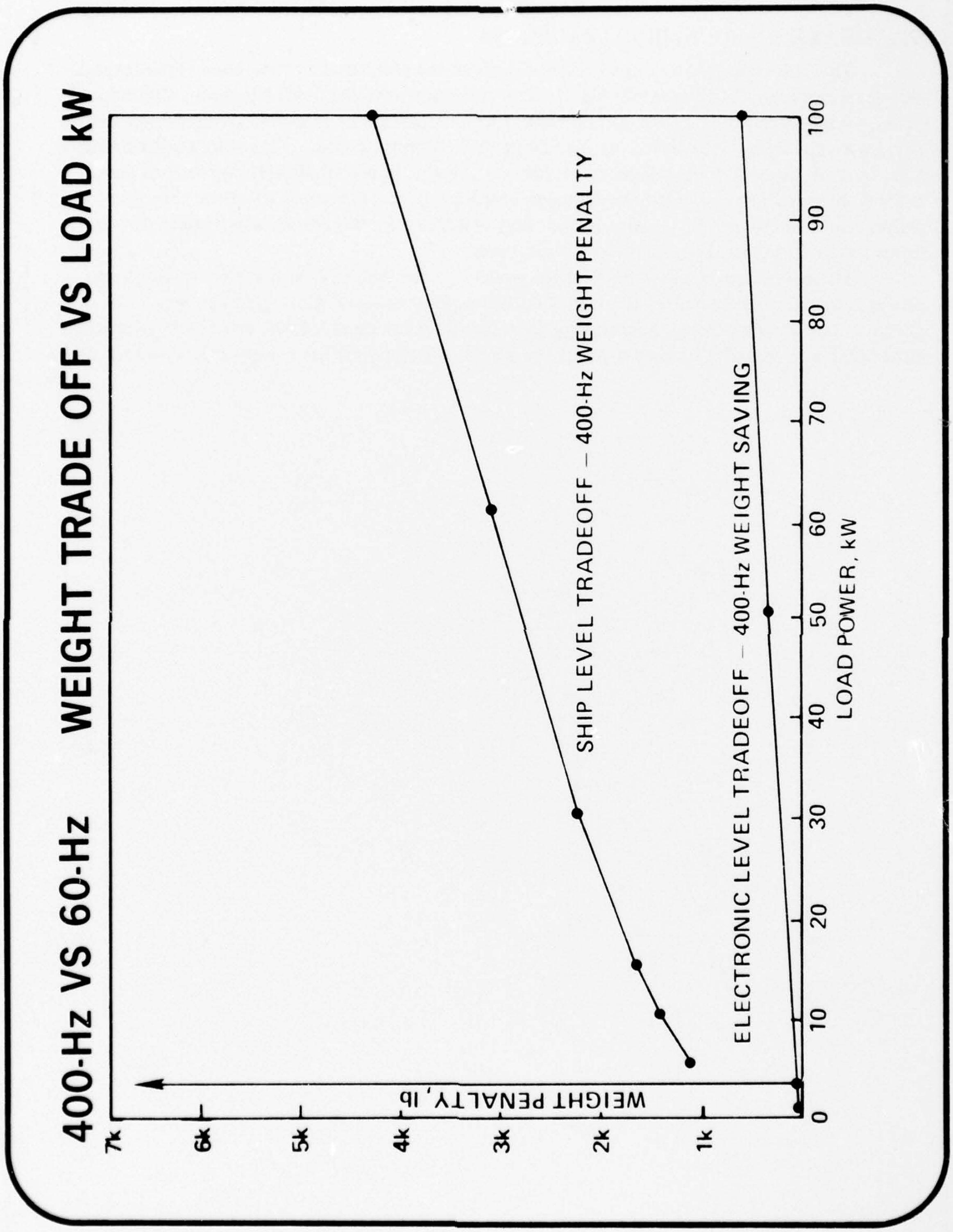
	60 Hz	400 Hz
TEMP RISE	80°C	150°C
REGULATION	2%	1.5%

Figure 7.

SYSTEM VERSUS EQUIPMENT TRADEOFFS

The difference between making tradeoffs at the electronic system level versus at the ship level can easily be illustrated (fig 8). The electronic-level tradeoff shows the difference in weight between 60- and 400-Hz transformers as a function of load kW. A moderate electronics weight saving is achieved by specifying 400-Hz input power. The more realistic ship-level tradeoff considers the weight of an MG set to provide 60- to 400-Hz conversion *minus* the weight saved in the electronics by using 400-Hz power. The tradeoff at the ship level shows a substantial weight penalty in the total system (ship plus electronics) where 400-Hz input power is specified for electronic equipment.

The soundness of choosing 400-Hz power for electronics in ships with 60-Hz prime power is questionable even for conventional technology using 60-Hz magnetics. Recent advances in power electronic technology that eliminate the need for line-frequency magnetics, either 60-Hz or 400-Hz, further support the specifying of 60 Hz for electronics on 60-Hz ships.



400-Hz VS 60-Hz WEIGHT TRADE OFF VS LOAD kW
WEIGHT PENALTY, lb
7k
6k
5k
4k
3k
2k
1k
SHIP LEVEL TRADEOFF – 400-Hz WEIGHT PENALTY
ELECTRONIC LEVEL TRADEOFF – 400-Hz WEIGHT SAVING
0
10
20
30
40
50
60
70
80
90
100
LOAD POWER, kW

Figure 8.

TECHNOLOGICAL IMPACT ON 400-Hz POWER FOR ELECTRONICS

Two trends in power electronics technology are impacting the historical preference of 400-Hz power for shipboard electronics.

First is the increasing use of switching mode power conversion techniques in electronic systems. The frequency of the switching is usually not related to the powerline frequency. The size and weight of the magnetics and filters are functions of the switching frequency, not the line frequency. Therefore, selecting 400-Hz power over 60-Hz power no longer results in a size or weight savings in the electronics.

Second is the use of switching mode techniques in the solid-state frequency changers that are replacing MG sets. These solid-state frequency changers do not inherently have the integrating characteristics provided by the mechanical inertia in MG sets. The new frequency changers protect the load from line transients and also act as harmonic filters. However, they provide little integration of load changes. Any change in load is mostly passed directly to the power source of the solid-state frequency changers (the 60-Hz power system). Frequency changers will be less effective for "hidden" filters than they are now.

SWITCHING MODE POWER CONVERSION

Figure 9 is a typical block diagram of the new switching mode method of power conversion. The emi filter provides the high frequency filtering needed to pass emi specifications, such as MIL-STD-461 CE03 (powerline conducted emission between 20 kHz and 50 MHz). The line frequency has little impact on the size of this filter. The three-phase ac power is then directly rectified to dc power with no intervening powerline transformer. The dc voltage is 155 V dc for a 115 V line-to-line ac input and 590 V dc for a 440 V line-to-line ac input. The peak-to-peak ripple is about 13 percent and has a frequency of 360 Hz for 60-Hz input power and 2400 Hz for 400-Hz input power. This dc voltage is then lightly filtered. The filter is determined by the characteristics of the switching regulator[21] rather than the powerline

[21] Middlebrook, RD, Input Filter Consideration in Design and Application of Switching Regulators, paper presented at IEEE Industry Applications Society Annual Meeting, Chicago, 11 October 1976

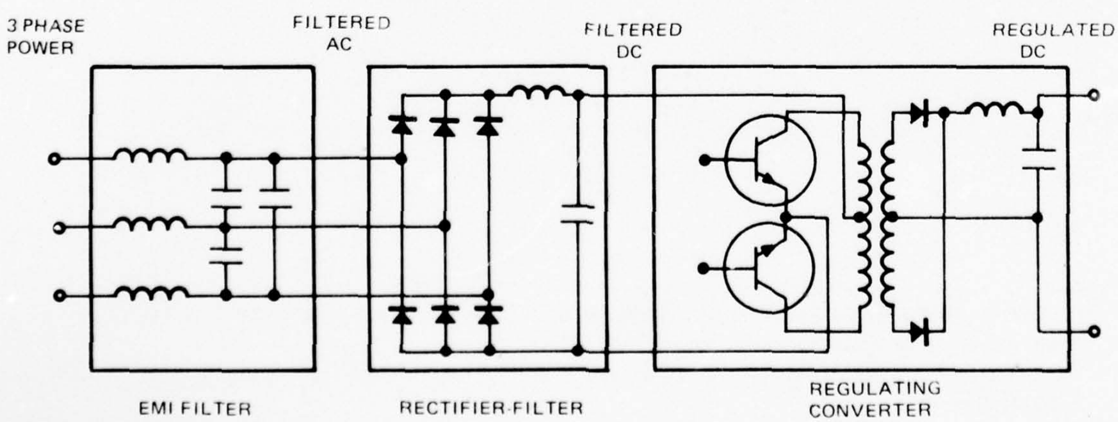


Figure 9. Switching mode regulator block diagram.

frequency, so that powerline frequency has no impact on the size of this filter. The 13 percent ripple is attenuated by the dynamic regulation characteristics of the regulating dc-to-dc converter. The dc-to-dc converter uses either solid-state thyristors or power transistors as the switching element. The switching frequency is determined by the state of the art and by the requirements of the system. Presently, the switching frequency is between 5 and 50 kHz for thyristors[22,23] and between 20 and 100 kHz for transistors.[24] The dc-to-dc converter contains the first transformer in the system, which provides transformer isolation between the power source and the load and transforms the voltage to required levels. The transformer size is determined by the switching frequency (5 to 100 kHz) and is independent of the line frequency (60 or 400 Hz).

The characteristics of this switching mode regulator negate the classical size and weight advantages of 400-Hz power over 60-Hz power since none of the filters or magnetics are related to powerline frequency.

The particular switching mode regulator shown in fig 9 is not used directly because there are new requirements to limit harmonic currents drawn by shipboard electronics. The power supply shown uses 6-pulse bridge rectification, as have most previous shipboard electronic power supplies. But 6-pulse rectification operating into an inductive input filter generates a 20 percent 5th harmonic current and a 14 percent 7th harmonic current. New shipboard specification limits require individual harmonic currents to be less than 3 percent of the fundamental current. One popular method of meeting this requirement is to use 12-pulse or 24-pulse rectification to eliminate the hard-to-filter lower order harmonics. Figure 10 compares harmonic currents from 3-pulse, 6-pulse, 12-pulse, and 24-pulse rectification, in an inductive input filter. Also shown is the new MIL-E-16400 specification limit. Line frequency power transformer windings can be interconnected to give the necessary phase shifts necessary for 12- or 24-pulse rectification. This method of reducing harmonics, however, reintroduces the powerline frequency transformer into electronic power supplies.

Other methods for reducing harmonic currents are discussed briefly later in this document under Harmonic Suppression and in more detail in appendix D. The best method of meeting the new harmonic current limits is still an open technical issue. Some of the harmonic current suppression techniques may again introduce a size or weight advantage to 400-Hz power over 60-Hz power that would have to be considered in tradeoff studies.

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[22]Driscoll, JC, High Current, Fast Turn-on Pulse Generation Using Thyristors, paper presented at IEEE Power Electronics Specialists Conference, 11 June 1974

[23]Hunt, SR, An Evolutionary Examination of Thyristor Device Characteristics, paper presented at Powercon 2, 17 October 1975

[24]Aswell, CJ, A New Monolithic Switching Regulator, paper presented at Powercon 3, 25 June 1976

HARMONIC CURRENTS(I_N) CAUSED BY RECTIFICATION AS A RATIO OF FUNDAMENTAL CURRENT (I_1) FOR VARIOUS SECONDARY RIPPLE (r) FACTORS

HARMONIC	I_N/I_1				
	r				
N	3	6	12	24	SPECIFICATION LIMIT*
2	0.50	–	–	–	0.03
4	0.25	–	–	–	0.03
5	0.20	0.20	–	–	0.03
7	0.14	0.14	–	–	0.03
8	0.13	–	–	–	0.03
10	0.10	–	–	–	0.03
11	0.09	0.09	0.09	–	0.03
13	0.08	0.08	0.08	–	0.03
14	0.07	–	–	–	0.03
16	0.06	–	–	–	0.03
17	0.06	0.06	–	–	0.03
19	0.05	0.05	–	–	0.03
20	0.05	–	–	–	0.03
22	0.05	–	–	–	0.03
23	0.04	0.04	0.04	0.04	0.03
25	0.04	0.04	0.04	0.04	0.027
26	0.04	–	–	–	0.025
28	0.04	–	–	–	0.022
29	0.03	0.03	–	–	0.020
31	0.03	0.03	–	–	0.018
THD	0.68	0.31	0.15	0.08	

* MIL - E - 16400G AMENDMENT 1

Figure 10.

FREQUENCY CHANGER FILTERING CHARACTERISTICS

Aboard 60-Hz ships, 400-Hz power has often been specified to take advantage of the filtering characteristics of motor-generator sets. The introduction of solid-state frequency changer technology requires reconsideration of their use. Frequency changers provide two types of filtering: harmonic and transient.

Harmonic filtering by frequency changers is essentially the same for both MG sets and solid-state sets. The motor characteristics of the MG sets determine the harmonic current drawn, almost independently of the prime generator and load. The input transformer-rectifier of a solid-state set determines the harmonic current drawn, almost independently of the dc-to-ac inverter section and load. Although a frequency changer is effective as a harmonic filter, a passive or active filter specifically designed for reducing harmonic currents would probably be smaller, lighter, more reliable, and more effective than a frequency changer.

Transient filtering by MG sets is very different from transient filtering by solid-state inverters. Energy for the MG set is stored as inertia of its rotating members, which is inherently present in the design. Additional energy storage can be provided with a flywheel. Energy for the solid-state set is stored in discrete inductors and capacitors. A normal design objective is to minimize these inductive and capacitive components and hence to minimize energy storage. Additional energy storage obtained by larger inductors and capacitors or, in the case of uninterruptible power supplies, by batteries is thus not inherent in the design for the solid-state set. Selecting 400-Hz power to exploit the energy storage and filtering in frequency changers – valid for MG sets – may be totally invalid for solid-state sets.

The best way to filter the effects of pulse loads reflecting into the power system and to keep major power system transients from affecting the load is still an open technical issue. The use of frequency changers for this purpose has probably never been an optimum solution and, when solid-state frequency changers replace MG sets, may not even be a workable one.

SUMMARY

A switching mode power conversion technology is available that is now being used in many Navy systems and that completely negates any size or weight advantage 400-Hz input power has in electronics. The only open technological questions are how best to attenuate harmonic currents and how best to filter pulse load currents and power system transients. The final solutions to these questions may or may not indicate size and weight benefits in the electronics if they are powered by 400 Hz rather than 60 Hz.

TOTAL COSTS OF FREQUENCY CHANGERS

The technical opportunity exists for eliminating the need for 400-Hz power on 60-Hz ships with no increase in size or weight of the electronics.

Given the technological opportunity, what is the cost impact both in monetary cost and in system costs (eg size, weight, reliability, and logistics)? These costs are now discussed.

The four ship studies delineated under Ship Electrical Power System Descriptions were used as a data base for determining the total costs associated with the 1546 MG-set frequency changers supplying 400-Hz power on 383 Navy surface ships. Total costs consist of monetary ones, referred to below simply as "costs," and nonmonetary ones, referred to as system penalties. The discussion would not be complete without a projection of future trends. A summary of these tradeoff factors is given in figure 11.

FREQUENCY CHANGER COST/PENALTY SUMMARY

- COSTS
  - ACQUISITION
  - MAINTENANCE
  - OPERATING FUEL
  - IMPROVEMENT PROGRAMS
- SYSTEM PENALTIES
  - SIZE AND WEIGHT
  - RELIABILITY
  - LOAD INTERACTIONS
- FUTURE TRENDS

Figure 11.

FREQUENCY CHANGER TRADEOFF FACTORS

COSTS

Costs are incurred for acquisition and replacement of MG sets and for their maintenance and operation. Installation or replacement of MG sets often requires opening of the ship's hull. Navy personnel training to maintain and operate MG sets has been unusually expensive because there are 195 different MG-set designs in the fleet. Costs relating to acquisition, maintenance, and operation (particularly fuel costs) are discussed later in more detail.

In addition to acquisition costs for frequency changers on surface ships, annual dollar costs are $4.4 million for fuel and $2.7 million for maintenance.

SYSTEM PENALTIES

Other costs are incurred in an effort to improve 400-Hz systems. The need for frequency changers has resulted in the installation of an average of four 60- to 400-Hz MG sets on each of 383 surface ships. Four MG sets weigh an average of 19 200 pounds (8.7 Mg) and occupy an average space of 240 cubic feet (6.8 m^3). MG sets have a high failure rate. They rank 73 in the top 300 Navy problem equipments. Load interaction problems are more prevalent with 400-Hz power systems than with 60-Hz power systems. But the current trend is to use more and more 400-Hz electronics despite these resultant high costs and system penalties.

FUTURE TRENDS

The 400-Hz connected loads in the first three ships studied were 8, 4, and 13 percent of the ships' respective total connected loads. Future costs and penalties will be affected by the trend to specify 400-Hz power for electronic equipment, a trend which will increase these percentages. This is commented on later.

ACQUISITION COSTS

Costs are incurred when frequency changers are installed either initially or on replacement. The costs are high because of the many MG sets used per ship. Up to 17 are required on a CG class ship, which carries a Terrier missile system. Other ships have as many as 33 MG sets. Installation of newer solid-state frequency changers should decrease the number of MG sets required by an as yet undetermined amount. Figure 12 lists the acquisition costs for MG sets.

Unit procurement is only part of the one-time acquisition costs. Installation or replacement of MG sets often requires opening of the ship's hull. For this reason, the Navy's standard solid-state frequency changers are being designed to go through 30- by 30-inch hatches and 26- by 45-inch doors.

Other acquisition costs are associated with engineering support, repair parts, and crew training. These costs, particularly those for crew training, are magnified by the 195 designs – and the 195 associated technical manuals – from 30 different manufacturers of the present 60- to 400-Hz MG sets in the fleet. Most of the newer MGs are being manufactured by only three companies. The Navy's standard solid-state frequency changers have been optimized for minimum life-cycle costs. For example, a single design configuration is used for all sizes. This standardization will greatly reduce training costs.

ACQUISITION COSTS FOR MG SETS

- Procurement of unit
- Installation
- Engineering services and support
- On-board repair parts
- Training crews

Figure 12.

MAINTENANCE COSTS

Maintenance costs are a large part of the overall 400-Hz system costs. Excessive maintenance costs have occurred because of the high MG failure rate and the complex logistics of supporting the many different MG set designs. To get and keep the MG sets going has required highly specialized teams from NAVSEA, NAVSEC, shipyard and support facilities, and the fleet.

A paper from NAVSEC 6156D discusses as follows the problems with the present system.[25] "For several years, there has been an expensive 400-Hz MG set 'fix' program. The problems were caused primarily by too many different MG set designs. The logistics of trying to support so many different designs become horrendous. Also, providing training to frequently changing personnel for each particular design of MG set and providing satisfactory documentation become so complex that highly specialized attention from many teams of people, from NAVSEA, NAVSEC, shipyard and support facilities, and from the fleet were required to get and keep the MG sets going."

One of the maintenance problems occurs from excessive brush wear due to lightly loading some ship service 400-Hz MG sets. On some ships, oversized MG sets are installed in anticipation of possible future 400-Hz load additions (eg, 100-kW MG set loaded with only 20 kW). To correct this problem, some of these oversized MG sets have been modified internally, either by removing some brushes or by other "fixes."*

A Navy 3M report entitled Logistic High Failure Equipment (ref 7c) ranks problem equipment with regard to maintenance factors – actions, ships' reporting data, total failures, man-hours, parts, deferrals, and hours down. Figure 13 lists such maintenance data for MG sets from the report for a recent *12-month period*. There were 215 actions in which repairs could not be performed by using existing ships' spare parts or assistance: outside parts were required for 36 actions and outside assistance for 179 actions. A total of 923 000 hours down was computed for the 376 total failures. For deferrals, the hours down are the number of hours to the closing action or end of the time frame (11/75), and for each nondeferral, 4 hours were added.

A discussion with the NAVSEC project engineer for 400-Hz motor generators disclosed that there are about 30 open (not yet repaired) casualties per month out of the total of 1546 MG sets on the 383 ships.*

Both MG specifications call for a maximum geometric mean-time-to-repair ($MTTR_G$) of 2 hours and equipment repair time (ERT) not to exceed 6 hours. The standard solid-state changer specification requires variable corrective maintenance times as follows:

Drawer replacement (restore power) – 10–25 min

Parts and PC boards replacement from drawer – 2–5 hours

Module or PC board ERT – 68 min

Maintenance costs are therefore expected to be much less for the standard solid-state frequency changers.

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[25] Henrickson, FR, The Future of 400-Hz Power Systems – Present Interface Problems and Solutions, paper presented at the Association of Scientists and Engineers 13th Annual Symposium, December 1975

*Personal communication from A Nickley, NAVSEC 6158C, to E Kamm, 5 February 1976, at NAVSEC, Hyattsville MD

RELIABILITY COSTS

RANK OF 60-400-Hz MG SETS IN TOP 300 PROBLEM NAVY EQUIPMENTS 12/74 - 11/75

FACTOR	DATA VALUE	FACTOR RANK
Maintenance actions – completed & deferred	714	77
Ships reporting maintenance data	362	43
Ratio of maintenance action to ships	2	301
Total failures status codes 2 or 3 – nonoperational or reduced capability	376	71
Man-hours (thousands)	10	67
Cost of parts (thousands)	62	297
Deferrals – both parts & assistance outside ship	215	62
Hours down (thousands)	923	57
Overall rank		73

Figure 13.

How much will it cost to maintain these shipboard MG sets over the next 10 or 20 years? To project future annual maintenance costs, a statistical analysis was performed for four diverse ship types. It used pre-July 1975 class designations so as to tie in with the cost data references.

The DE 1040 class was included to provide more representative statistical data. (Since it does not have high-power radars or missiles like the other classes, its inclusion results in a better cross section of ships that use MG sets.) The CV class was excluded because it has only a few ships and low uniformity of armament and radars.

The components of annual maintenance cost – scheduled and corrective maintenance parts and labor, as well as overhaul costs – were totaled for each of the 3 years, FY 73, FY 74, and FY 75. A NAVSEC study provided the labor rate: $20 per hour for FY 75, deflated 10 percent per year for FY 74 and FY 73.[26] This rate includes ship, tender, and some shipyard support costs. The three totals were time plotted, and a least-squares line was fitted to each set of points (fig 14). Any improvement in maintenance would tend to depress the slope of the lines. The 10 percent yearly inflation rate would tend to elevate the slope. The data show the net effect of FY 1973 through 1975 maintenance improvements and inflation to be an increasing cost.

Similar graphs based on one higher labor rate and one lower one were plotted to show the sensitivity of the total cost to a change in hourly labor rate. These graphs are shown in appendix A.

Appendix A describes the statistical study in more detail, giving the methodology, assumptions, and sources for each cost category.

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[26]Naval Ship Engineering Center letter 6158E/JKM 9610-4 ser 2378 to Naval Sea Systems Command, Subject: 400-Hz Modified Central Power Systems on the DLG 16, 26 and CGN 9 Classes, Life Cycle Cost Study of, 1 July 1975

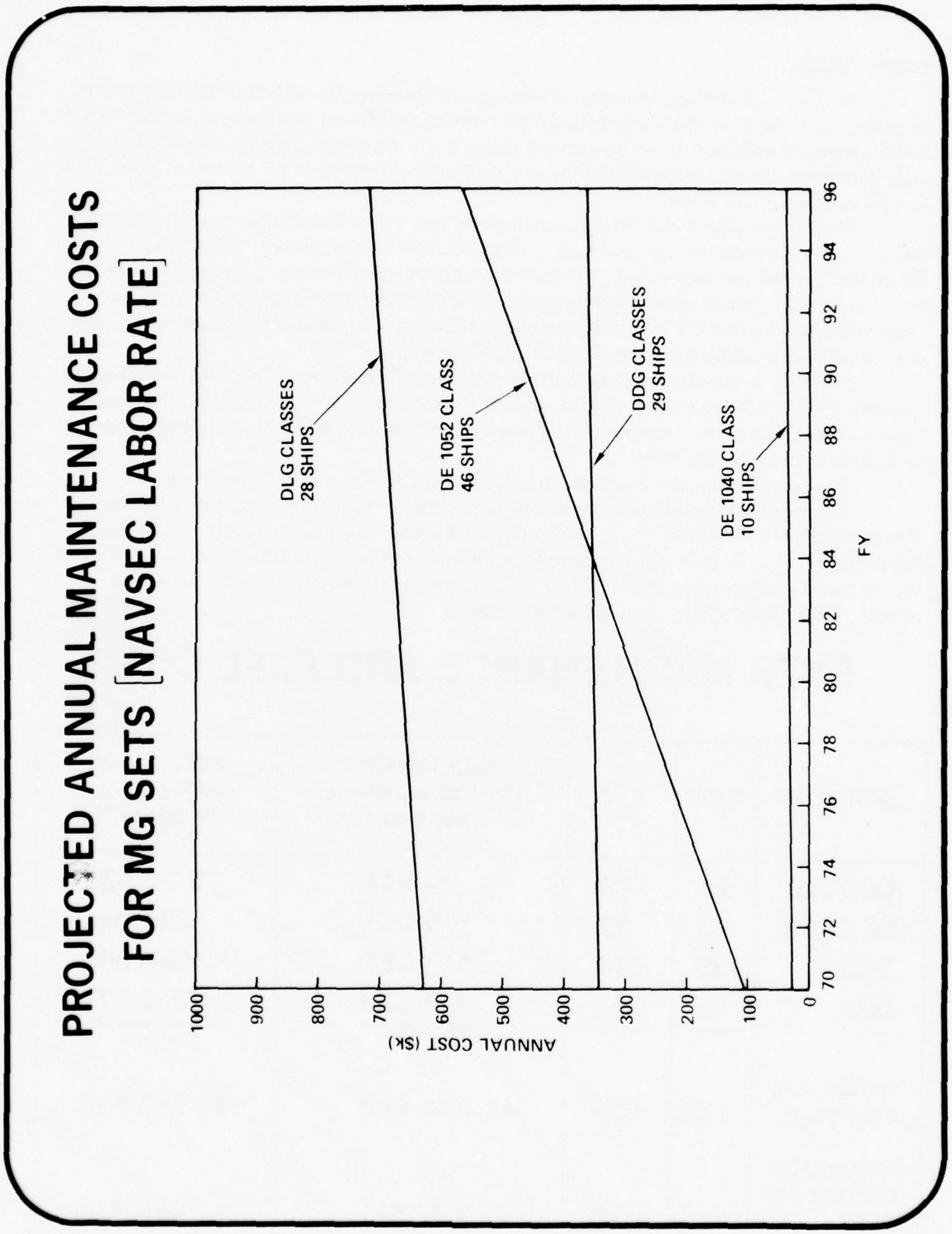
PROJECTED ANNUAL MAINTENANCE COSTS
FOR MG SETS [NAVSEC LABOR RATE]
ANNUAL COST ($K)
0
100
200
300
400
500
600
700
800
900
1000
FY
70
72
74
76
78
80
82
84
86
88
90
92
94
96
DLG CLASSES
28 SHIPS
DE 1052 CLASS
46 SHIPS
DDG CLASSES
29 SHIPS
DE 1040 CLASS
10 SHIPS

Figure 14.

FUEL COSTS

Fuel costs are among the main operating cost components of 400-Hz electric power systems, partly because of the low efficiency of shipboard MG set frequency changers – 66 to 88 percent at full load, 61 to 85 percent at half load. By comparison, the Navy's solid-state frequency changer is specified to have a minimum efficiency of 80 percent at rated loads and 70 percent at half loads.

What is the cost of the extra fuel consumed due to the low efficiencies of shipboard MG sets? Annual costs for the additional fuel attributable to the inherent power losses of 60- to 400-Hz MG sets were computed for the four selected ship types. The ships' steam turbines require 0.9 pounds (0.405 kg) of marine diesel fuel (DFM) per kilowatt-hour. The average cost of the fuel (1976) is $26 per barrel delivered. On the basis of these figures, the cost of DFM was calculated to be $0.0785 per kilowatt-hour.

Pertinent parameters such as individual MG set efficiencies and annual kilowatt-hours consumed by each MG set were also calculated. Consideration was given to the effects of various operating modes – anchor, shore, cruising, and battle conditions – on load factors and proportionate annual hours.

The assumptions, data sources, and calculations are detailed in appendix B.

A comparison based on the four ship types analyzed (fig 15) shows that total annual fuel costs ($1 943 596) are 162 percent of the total annual maintenance costs ($1 200 689). Projecting these costs to all surface ships with MG sets yields an annual fuel cost of $4 438 404 and an annual maintenance cost of $2 737 571. Since fuel costs appear to be increasing rapidly, future costs will be correspondingly higher.

FY75 MAINTENANCE AND FUEL COSTS

SHIP CLASS	SHIPS	MG SETS	MAINTENANCE FY75 USING NAVSEC LABOR RATE	FUEL DUE TO INEFFICIENCY OF MG SETS
DE 1040	10	20	$ 29 944	$ 12 938
DE 1052	46	92	195 053	294 046
DDG	29	214	343 053	404 841
DLG	28	351	632 639	1 231 771
TOTALS FOR 4 CLASSES	113	677	$1 200 689	$1 943 596
TOTALS FOR ALL SURFACE SHIPS	383	1546	$2 737 571	$4 438 404

Figure 15.

These operating fuel costs are augmented by the indirect cost of the ships' added cooling system loads imposed by heat losses in the MG frequency changers. This necessary added cooling system capacity requires its share of equipment, maintenance, and electrical power (with its associated fuel cost).

IMPROVEMENT PROJECT COSTS

The Navy has been trying to solve 400-Hz power-system problems for many years. To strengthen and coordinate some of these efforts, NAVSEC began a program in June 1973 called "Improvement of 400-Hz Power System and Weapon Systems Interface." Various aspects of this and other specific programs are described below. The results of extensive studies and shipboard tests indicate small hope of making MG set improvements that will lower their costs. Although not yet demonstrated, the design goal is to lower life-cycle costs by replacing MG sets with solid-state frequency changers.

The aim of the NAVSEC program was to investigate, identify, and take corrective action on electrical interface problems found in the Fleet.[27] Test teams from NAVSEC (Philadelphia), NSWSES (Port Hueneme, CA) and NSRDC (Annapolis) have tested the 400-Hz systems on five ships: USS LEAHY (DLG 16), USS COLUMBUS (CG 12), USS BOWEN (DE 1079), USS DECATUR (DDG 31), and USS CHICAGO (CG 11). The NSRDC team also performed a sixth test on USS GRIDLEY (DLG 21). Pre-July 1975 class designations are used to correspond to testing dates.

Test results indicate that some 400-Hz power systems with multiple loads operate satisfactorily and are within the requirements of MIL-STD-1399, Section 103. However, there are many loads which require dedicated MG sets. These loads usually (but not always) operate satisfactorily even though the power system sometimes operates outside specification requirements. Large nonlinear and pulsating electronic equipment sets are the major loads responsible for power-system degradation. They cause power-system modulation to exceed MIL-STD-1399 specifications and/or create excessive waveform (usually harmonic) distortion.

Various aspects of the program to correct these problems are next described.

Design improvement studies were performed to improve MG response to pulsating loads. This effort was found to be unpromising.*

Since better line filters would eliminate some of the needs for MG sets, actions have been taken to obtain better passive and active filters. NSRDC has developed an energy storage unit (ESU) passive filter, and a brass-board model of it has been tested on several ships.** NAVSEC has contracted to develop an active filter. The current filter design is deficient at higher frequencies and must be made smaller and lighter.*

Extensive shipboard studies showed that better test equipment and methods were needed to define power-system problems. Consequently, NSRDC developed a portable solid-state dynamic load simulator having nonlinearity and pulsing characteristics of major 400-Hz loads.[27,**] NOSC developed a better test methodology which determines the susceptibility

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[27] Spivack, M, 400-Hz Power Systems and Weapon Systems Electrical Interface Improvement, NAVSEA Journal, v 23, no 11, p 34-35, November 1974

*Telecon between E Kamm, NOSC 7434 and M Spivack, NAVSEC 6156D, on 10 June 1976

**Telecon between E Kamm, NOSC 7434 and J Goodman, NSRDC 2781, on 10 June 1976

of electronic equipment to powerline anomalies such as modulation, harmonics, and variations of voltage and frequency.[28,29]

Studies and tests were performed to evaluate the potential benefits of centralizing 400-Hz power systems (either partially or completely). The advent of the solid-state frequency changer (SSFC) gave impetus to these centralization studies since it appeared that SSFCs provide faster voltage regulation and lower source impedance than MG sets. The results (detailed in appendix C) indicate that the life cycle costs are higher for centralized systems than for existing MG systems for the DLG 16, DLG 26 and CGN 9 classes. Short term tests aboard USS TRUXTUN indicated that SSFCs may require fewer dedicated MG sets, but problems still remain (appendix C).

A working group of representatives from both Navy and industry was formed for the purposes of establishing electronic and weapon system design criteria, modifying specification requirements, and serving as a technical group for the interchange of 400-Hz power-system information and problems.[30]

As indicated previously, the SSFC alleviates some of the problems associated with MG sets. Solid-state frequency changers are beginning to replace shipboard MG sets and can be expected to totally replace them in time. However, the mechanical inertia of MG sets results in better isolation for pulsating loads than is provided by SSFCs.*

The development of a family of SSFCs by the Navy is still another example of an effort to resolve 400-Hz system problems. A program that will result in prototype units is nearing the end of the second of three phases. The program has been planned to reduce life-cycle costs by avoiding the many problems of reliability, maintenance, logistics, and training that are associated with MG sets. However, the specifications indicate only a slight advantage in weight, volume, and power loss over comparably rated MG sets.

WEIGHT AND SIZE PENALTIES

A primary purpose of going to 400 Hz in the past was to save weight and space in the electronics equipment. But because frequency changers were then required, the overall result was to increase total ship weight and size.

As shown in Table 1, weights for MGs specified by MIL-M-19633B can vary from 1200 pounds (540 kg) to 17 500 pounds (7900 kg), and volumes can vary from 19.5 cubic feet (0.6 m^3) to 209.4 cubic feet (5.9 m^3). MGs specified by MIL-M-19160C are somewhat lighter and smaller. The standard solid-state frequency changers are not much of an improvement with regard to space and weight – SHIPS-F-5637A specifies weights varying from 1100 to 11 000 pounds (500 to 5000 kg) for various sizes with volumes from 21 cubic feet (0.6 m^3) to 280 cubic feet (7.9 m^3). SHIPS-F-5637A is the NAVSEA contract specification for 10–250 kW solid-state frequency changers.

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[28] Naval Electronics Laboratory Center Technical Note 2946, Susceptibility of Electronic Equipment to Power Source – Tests on AN/SRC-31, by E Kamm and TA Danielson, 16 July 1975 (NELC and NOSC Technical Notes are working documents and do not represent an official policy statement of NOSC)

[29] Georgia Institute of Technology Report TR-1725-2, Power Susceptibility Test Planning for AN/SPG-55B Radar, by E Kamm (NOSC), JJ Heckman, EE Donaldson, and JA Scheer, 30 October 1975

[30] Naval Ship Systems Command letter SHIPS 423, Serial 2192, to Naval Ordnance Systems and Naval Electronic Systems Command, Subj: 400-Hz SMS Power Source – Load Interface Meeting, 12 June 1974

*Telecon between E Kamm, NOSC 7434, and H Wong, NAVSEC 6158D, on 16 March 1977

TABLE 1. MAXIMUM WEIGHTS AND VOLUMES FOR SHIPBOARD MG SETS.

Rating, kW	Weight, pounds(5) MIL-M-19160C General Purpose(1)	MIL-M-19633(2) General Purpose	MIL-M-19633(2) Special Purpose(3)	Volume, cubic feet(6) MIL-M-19160C General Purpose(1)	MIL-M-19633B(2) General Purpose	MIL-M-19633B(2) Special Purpose
5	1200	1200	1400	16.2	19.5	21.8
10	1500	2100	2300	21.0	30.3	32.7
15	1800	2300	2600	22.9	31.4	33.8
30	2500	3300	3800	29.7	45.8	58.2
60	3600	5300	5900	42.4	73.4	88.9
100	5000	7400	–	55.1	92.0	–
100(4)		8400			99.5	–
200	9000	12 400	–	110.4	172.4	–
200(4)		14 400			188.2	–
300	10 000	15 500	–	117.8	193.7	–
300(4)		17 500			209.4	

(1) voltage regulated
(2) voltage and frequency regulated
(3) with voltage balance regulators
(4) water cooled
(5) divide by 2.2 to convert to kg
(6) divide by 35.3 to convert to m^3

The weight penalty is always much more than the weight savings when 400 Hz is used aboard a ship. A comparison of the penalty versus savings is shown for various 400-Hz power requirements in figure 16.

The curves were obtained by first plotting minimum and maximum data points of both weight savings and penalty, at a power requirement of 200 kW. Because higher power requirements were assumed to require proportionately more weight, the curves were extrapolated as straight lines. The minimum weight savings line was obtained from the weights of two 100-kVA transformers. The maximum weight savings line represents mixes of smaller transformers, filters, and other electronic components. Plotted points for both weight penalty curves show the combined weights of two 100-kW MG sets. The minimum curve reflects the weights of the lighter MG sets (MG specification MIL-M-19160C); the maximum, the heavier MG sets (MG specification MIL-M-19633B).

Specific MG weight data for three ships is plotted to validate weight cost curves. USS DOWNES (FF 1070) requires 200 kW of 400-Hz power; its MG sets weigh 14 800 lb (6.7 Mg). USS BERKELEY (DDG 15) supplies 470 kW of power with 30 700 lb (13.9 Mg) of MG sets. And USS HALSEY (CG 23) can supply 12 600 kW of 400-Hz power with its 66 600 lb (30 Mg) of MG sets. These diverse examples are well within the range of the general weight penalty curves.

The assumption that using 400-Hz electronics saves shipboard weight is invalid. In fact, when 400-Hz power is used for electronics on ships having 60-Hz primary power, from four to ten times as much weight is added to the ship as is saved in electronics equipment.

SHIPBOARD WEIGHT COST VERSUS WEIGHT SAVING USING 400-Hz POWER INSTEAD OF 60-Hz POWER

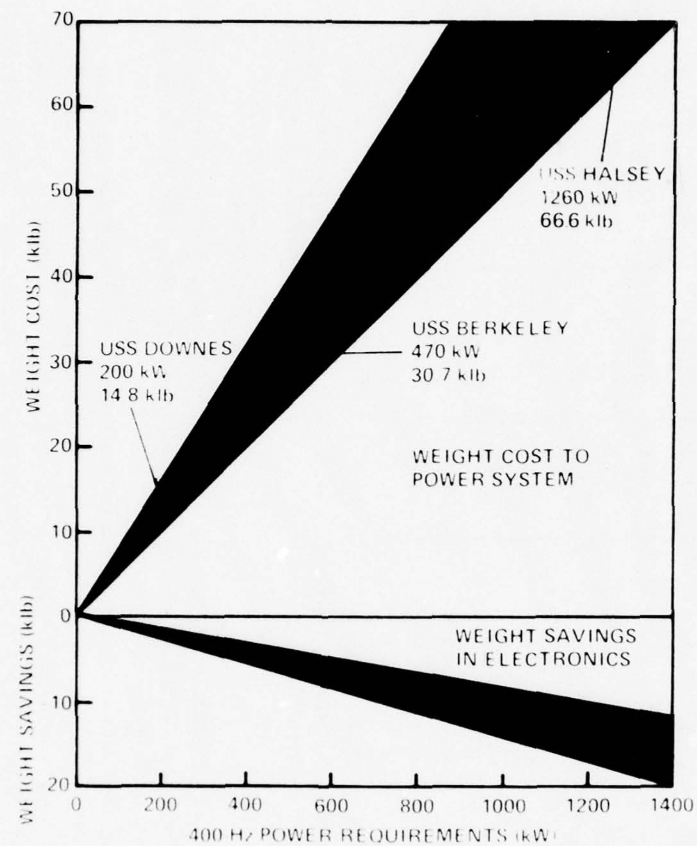

Figure 16.

RELIABILITY PENALTIES

Since the 400-Hz power system requires 60-Hz input for operation, 400-Hz ship service power is always a less reliable source than 60-Hz ship service power. The difference in reliability depends on frequency changer failure rate. MG sets have a history of poor reliability. They ranked 73 in the top 300 problem equipments of the Navy during a recent 12-month period.

Navy problem equipments are ranked in a 3M report entitled Logistic High Failure Equipment. Figure 13 is an excerpt from this report and ranks MG sets with regard to maintenance factors. The overall ranking is arrived at by giving equal weight to each factor. The poor reliability of MG sets has contributed to the use of a large number of them either in parallel or as standby sets. This redundancy insures continuous availability of 400-Hz power, but at a high price.

Solid-state frequency changers perform the frequency changing function with no moving parts and are therefore potentially more reliable and maintainable than MG sets. Replacing MGs with SSFCs should improve the reliability of frequency changers.

LOAD INTERACTIONS

Many shipboard MG sets are dedicated to single electronic loads to preclude interference that occurs between loads fed by a common MG. Such interference can be caused by one load's creating powerline distortions which degrade the performance of other susceptible loads (fig 17). Harmonic or pulse currents drawn by loads cause voltage drops across the source impedance, generating corresponding harmonic or modulating voltages in the entire power system.

The Navy has conducted many shipboard tests to investigate, identify, and take corrective action on these 400-Hz electrical interference problems. Specific examples are discussed later. Test teams from NAVSEC, Philadelphia, NSWSES, Port Hueneme, Calif., and NSRDC, Annapolis have extensively tested 400-Hz power-system and weapon-system interfaces on Navy ships and have found that large nonlinear and pulsating electronic equipment sets are the major loads responsible for interference problems.

The source impedance of shipboard 400-Hz generators is greater than that of 60-Hz generators primarily because the former have lower kilowatt ratings. (Shipboard 400-Hz power requirements are only about one-tenth those of 60-Hz power.) In addition, 400-Hz system impedance is somewhat higher because of the higher reactance of the power distribution lines. The result is higher harmonic and modulation voltages on 400-Hz systems for equal distortion currents.

Impedance and coupling problems are greater for 400-Hz systems than for 60-Hz systems. Dedicated MG sets are commonly used to reduce impedance coupling. The mechanical inertia of an MG set acts as an integrator or low-pass filter. This serves both to protect the power source from load transients and to protect the load from power-source transients. An MG set will also isolate load harmonic currents from the source, thereby acting as a harmonic current filter. MG sets are often dedicated to specific equipments to serve this filtering function.

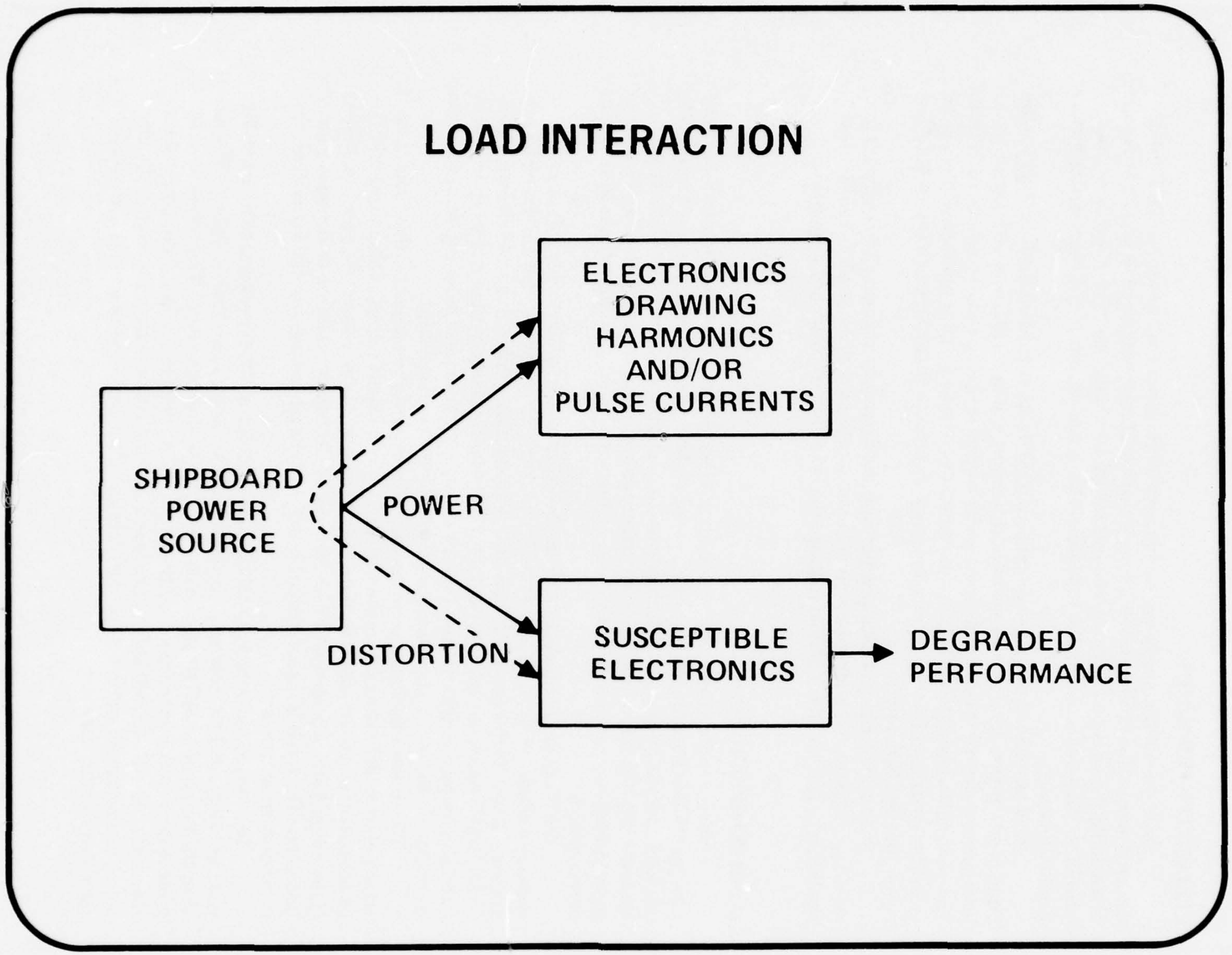
LOAD INTERACTION
SHIPBOARD POWER SOURCE
POWER
DISTORTION
ELECTRONICS DRAWING HARMONICS AND/OR PULSE CURRENTS
SUSCEPTIBLE ELECTRONICS
DEGRADED PERFORMANCE

Figure 17.

FUTURE TRENDS

Will future costs of 400-Hz systems increase or decrease?

Unfortunately, the proportion of 400-Hz electronics on Navy ships is increasing. If this trend continues, the costs to the Navy will rise considerably rather than decrease, even if MG sets are replaced by SSFCs. The electronic manufacturers' rationale for using 400 Hz has long been the size and weight advantage.

The impact of this increasing trend toward 400-Hz electronics is a continuing Navy requirement for more and more shipboard frequency changers and a continuing rise in associated maintenance and operation costs. New ships will need proportionately more space reserved for frequency changers and will have to be designed to carry this additional weight. Load interaction problems will become more severe as more 400-Hz loads are added.

Future costs will increase if no corrective action is taken. If other factors were constant, standard SSFCs and more centralized 400-Hz systems would tend to reduce costs. But since the other cost factors due to the increasing trend (fig 18) will probably be greater, the net result will be a cost increase.

FUTURE

TRENDS

- INCREASING USE OF 400 Hz

UNLESS TREND REVERSED

- MORE FREQUENCY CHANGERS
- MORE ACQUISITION, MAINTENANCE, AND OPERATING COSTS
- MORE SHIPBOARD SPACE AND WEIGHT REQUIREMENTS
- MORE LOAD INTERACTION PROBLEMS

Figure 18.

TECHNOLOGY FOR FREQUENCY-INDEPENDENT ELECTRONICS

The progress of technology has been shown to negate the historical size and weight advantage of using 400-Hz power in preference to 60-Hz power in electronic equipment. Technology is available to design electronic equipment that is independent of the frequency of the power source. If electronic equipment does not operate from the same frequency as the source power, frequency changers must be used between the electronic equipment and the prime power source. The cost of these frequency changers has been shown to be high from all cost aspects, including initial procurement costs, on-board repair parts, engineering services and support, installation, crew training, reliability, maintainability, space and weight, performance, and fuel costs.

The following sections discuss in greater depth the technology that can be used to make electronics independent of the power source frequency with no increase in size or weight.

The arguments presented so far indicate that a return to 60-Hz magnetics would provide a better total (ship-electronic) system than one using 400-Hz electronics with frequency changers, even though such a return would result in increased size and weight of the electronics. However, an alternate option, already being used for other reasons, would be to apply switching regulator technology. This would allow electronics to operate from 60-Hz power (and 400-Hz power) by means of power conversion circuitry that is smaller and lighter than conventional 400-Hz power conversion circuitry. This technology is discussed in detail. The frequency dependence of electromechanical components is also discussed.

SWITCHING REGULATOR TECHNOLOGY

A technological revolution has taken place in recent years in the field of ac-to-dc and dc-to-dc power conversion. The technology responsible for this revolution is termed switching regulator technology. Advances in components and analysis techniques have been combined with new and old circuit concepts. Switching regulator technology has yielded increased efficiency (less power loss) and decreased size, weight, and cost of power-conversion equipments.

POWER SUPPLY FUNCTIONS

A power supply is essentially a buffer circuit that matches a load to its power source. The power source typically is a ship service turbine generator that provides 3-phase 60-Hz 450-V ac power as defined by MIL-STD-1399, Section 103. A common example of an electronic load is an equipment's 5-V dc logic circuits. Almost all power in electronics is eventually used as dc power. A system design consideration is to minimize the impact of the power supply function on system figures of merit such as size, weight, reliability, source power, cooling requirements, and cost. Ideally, for a load compatible with the source, the power supply function would be served merely by interconnecting wires. Usually, the power supply function is more complex, requiring conversion and regulation of various electrical characteristics.

Figure 19 lists the power supply interfaces commonly used in the Navy.

Power supply regulator circuits and power conversion circuits can be either dissipative or lossless (fig 20). Dissipative regulators, by design, draw more power from the source than they deliver to the load. The undelivered power is converted to heat and removed by a

POWER SUPPLY INTERFACES

Power Source	Power Supply	Electronic Load
Shipboard systems (MIL-STD-1399)	A buffer element that matches load to source	Digital
Aircraft systems (MIL-STD-704)		Analog
Shore systems		Radar
Ordnance		Sonar
		ECM

Figure 19.

POWER SUPPLY CLASSES

- Dissipative Regulators
  - Shunt example
  - Series example
- Lossless Regulators
  - Ferroresonant example
  - Switching examples
    - Shunt (flyback)
  - Series

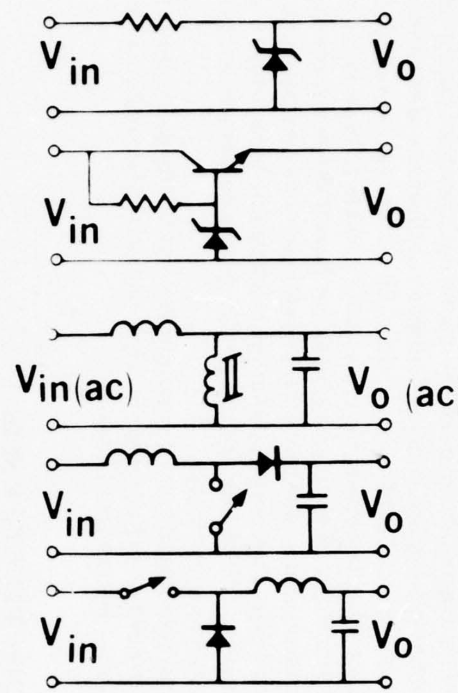

Figure 20.

cooling system. Familiar examples are the zener diode shunt voltage regulator and the transistor series voltage regulator.

In lossless regulators, the power delivered to the load equals that drawn from the source. Neither the regulation nor the conversion function, by itself, absorbs power. Power "losses" (conversion to heat, which is wasted) are caused by less than ideal components. Examples of lossless regulators are ferroresonant transformers and switching regulators.

Switching regulators using semiconductor switches have been used since the 1950s. They were commonly applied in many aerospace applications in the 1960s and became well established in commercial application in the early 1970s. Of the various types of switching regulators, those that are proving the most useful operate from dc input power, obtaining dc by direct (no transformer) rectification of the ac lines if the power source is ac. Power conversion is then accomplished by off-on modulation of a semiconductor switch operating at a frequency higher than normal powerline frequencies. Modulation is usually in the 10-100 kHz range. This technology can provide power conversion equipment that is independent of powerline frequency.

Various power supply configurations are first briefly discussed in relation to frequency independent power conversion. Then one particular configuration – switching mode regulators – is discussed in detail.

TRANSFORMER RECTIFIER SETS

The power supply configuration most used to power electronic loads is a transformer rectifier (TR) set followed by a low pass filter. If regulation is required, a dissipative transistor series regulator follows the low pass filter. The configuration is shown in figure 21. This configuration has several advantages, the most important ones being its low cost due to the simplicity of the design, the volume of supplies made, and the size of the competitive market. There are well over 200 sources from which they may be easily procured. The simplicity of the design helps in achieving reliability. Also, the high-volume usage makes the use of voltage regulator integrated circuits practical and yields additional reliability gains. With very small impact in size, cost, weight, etc, the 60-Hz configuration can be designed to operate from 50-, 60-, or 400-Hz sources and either 115- or 230-V inputs. The impact of these options on a 60-Hz design is so small that these features are provided as standard by some manufacturers.

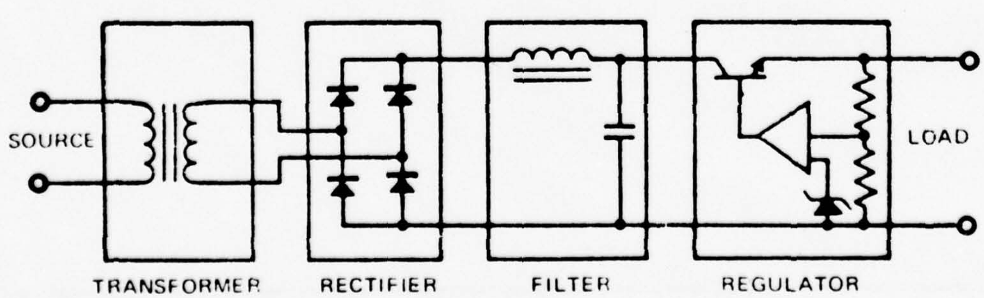

Figure 21. TR set and regulator power supply configuration.

Another advantage of this configuration is the relatively low amount of electromagnetic interference (emi) generated. The major sources of high-frequency emi are the recovery characteristics of the rectifier diodes and the sharp current rise and fall times caused by an inductive input filter. Low-frequency emi (line frequency and the first several harmonics) is caused by the nonlinear characteristics of the transformer and the rectifiers. Another advantage is the ease with which good dc and ac isolation between input ground and output or signal ground is achieved.

The disadvantage of the configuration lies in the size and weight of the 50/60-Hz transformer and the inefficiency of the dissipative regulator, if one is needed. Transformer weight varies inversely as the 3/4 power of frequency.[20] A 50/60-Hz transformer is almost 4.75 times the weight of a 400-Hz transformer. Dissipative regulators perform regulation by a voltage-to-heat conversion. As the source voltage tolerance increases, the size and weight of the heat conversion components and the extra power taken from the source (and dumped into the cooling system) soon become excessive. Another disadvantage is that there is no convenient method of tying in a redundant source of power if output power is required during a loss of the primary power source. This is a critical requirement in some present military systems and can be expected to become a more common requirement in the future.

The presence of the line frequency transformer makes the size and weight of this configuration dependent on the power source frequency for which it is designed.

TRANSFORMER TAP SWITCHING

Switching the input source to various taps on a transformer is a method that can be used for regulation. For fixed loads and stable sources, the proper taps can be selected during installation of the equipment. For more variable conditions, a variable tap (variable autotransformer) can be used and adjusted either manually or by a closed loop servo system. Also proper taps can be switched in as required in a closed loop feedback configuration.[31] The advantages of transformer tap switching include the preservation of near-unity power factor, high efficiency, and relatively small increase in transformer size. The major disadvantages are usually associated with complexity and regulation response time.

FERRORESONANT REGULATORS

An alternate method of power conversion in use is the ferroresonant transformer, of which there is a trademarked variation called the Paraformer.[32] Its prime advantages are great simplicity, potentially high reliability, and high efficiency due to its ability to provide regulation without a dissipative regulator. It also has inherent short-circuit protection. Its disadvantages are that it will operate only at one power source frequency and is about 50 percent larger than a conventional combined TR set and dissipative regulator. Again, there is no convenient method for using a redundant input source. The presence of a line frequency transformer makes the size and weight of this configuration dependent on the power source frequency for which it is designed.

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[31] Navy (NELC) Contract N00953-75-M-A007 with Parko, Santa Ana CA, Parko Drawing 101164, Miniature Power Supply

[32] Wanlass, SD et al, The Paraformer – A New Passive Power Conversion Device, Engineer/Scientist, October 1968

LINE FREQUENCY SCR REGULATORS

Regulation in this method is achieved by rectification of an ac input by means of a silicon-controlled rectifier (SCR) bridge in which the firing angle of the SCR is delayed so that the average output voltage is equal to or less than the average input voltage. An example is the light dimmer switch widely sold for home use. If it is used without a transformer, isolation between input and output grounds is lost. Also, the late firing angle for low-voltage supplies gives a very low power factor. If an SCR regulator is used with a transformer, the only advantage over TR sets with dissipative regulators is better efficiency. The disadvantages are higher emi and a poor power factor, with no savings in size or weight except as permitted by the increased efficiency. Again, there is no convenient method for using a redundant input source. The presence of a line-frequency transformer and line-frequency filters makes this configuration dependent on the power source frequency for which it is designed.

SWITCHING MODE REGULATORS

Power conversion in this method is obtained by direct rectification of an ac source to dc and then use of a regulating dc-to-dc converter operating at higher than line frequency to provide the output. Where the input is already dc, rectification and filtering are not necessary. The advantages are small size due to the use of high-frequency transformers and filters, high efficiency – even with a wide-tolerance input voltage – and a simple method of tying in redundant power sources. The disadvantages are high emi, great complexity, and in some cases high cost. Even when the prime power source is dc, a dc-to-dc converter is required. These converters already have the listed disadvantages of high emi, great complexity, and high cost. Therefore, switching regulators have few additional disadvantages.

Switching regulators can use any kind of on-off switching element such as transistors, silicon-controlled rectifiers (SCRs) with some type of forced commutation turn-off circuit, and gate turn-off devices (similar to SCRs except that they can be turned off as well as on by a gate).

The transistor switching regulator is being increasingly used to provide dc output voltages from a single-phase, 60-Hz source. Virtually every major power supply company now has switching regulators as part of its standard power supply line. The advantages of small size and high efficiency are proving to offset their sometimes high cost and emi in many commercial and military applications.

Cost projections show a crossover point between switching regulators and dissipative regulators as output power increases. Switching regulators are often more cost-effective in powers over 500 W to 1 kW, and the crossover point is becoming lower with time. Switching regulators in the 50- to 500-watt range are now only about 30 percent more costly than dissipative counterparts from the same manufacturer.

SWITCHING MODE POWER CONVERSION AND REGULATION

GENERAL DESCRIPTION

The scope of this discussion is limited to a class of high-efficiency switching mode power conversion circuits that operate from a dc input source or from a rectified ac source. A defining characteristic of the class is that the frequency of the ac input source has a

negligible influence on size and weight. A general block diagram of this circuit class is shown in figure 22.

The input emi filter is usually designed to attenuate the high-frequency noise caused by power semiconductor switching in the inverter/converter and by commutation of the rectifying diodes. Its size and weight are independent of the powerline frequency.

The rectifier block converts ac power to dc power. A six-diode three-phase bridge rectifier (6-pulse rectification) produces a dc voltage whose average is about 1.34 times the line-to-line ac rms input voltage. The ripple frequency is six times the line frequency, and the peak-to-peak ripple voltage is about 14 percent of the average dc voltage.

The nonlinear rectification process generates harmonic currents whose amplitudes fall off as 1/n of the fundamental amplitude, where n is the number of the harmonic. Only certain harmonics, determined by the number of rectifying pulses in a cycle of the fundamental, are present. For the six-pulse three-phase bridge rectifier the harmonics present are the 5th, 7th, 11th, 13th, 17th, 19th, ... If these harmonics must be attenuated, a harmonic filter is required. The size and weight of the rectifier portion of the block are independent of powerline frequency. If a harmonic filter is required, its size and weight depend on the powerline frequency.

At the output of the rectifier, the power is dc. If the switching regulator operates from a dc power source, power is brought into the circuit just ahead of the input filter and the previous blocks are not used. This dc point in the circuit, sometimes called a dc link, is an advantage if uninterruptible power is a system requirement.

The input filter is designed to attenuate the noise at and above the fundamental inverter/converter switching frequency. Its size and weight are determined only by the inverter/converter design and are independent of powerline frequency.[21]

The regulating inverter/converter block is the heart of the circuit configuration. If the required output is ac, the circuit is a dc-to-ac inverter. If the required output is dc, the circuit is a dc-to-dc converter. Since most power in electronics loads is dc power, the remaining discussion will concentrate on regulating dc-to-dc converters. Very little ac power is required in the electronics, but the technology for both inverters and converters is similar. Also similar is the switching mode technology used for motor control, heat regulators and other functions. The power switches in the inverter/converter can be bipolar transistors, solid-state thyristors (also called silicon controlled rectifiers or SCRs) or gate turn-off thyristors (similar to solid-state thyristors except that the gate can be used to turn the device off as well as on). Also used on occasion are less common devices such as tunnel diodes, MOS transistors, and Ovionic switches.

The size and weight of inverters depend on the required output frequency, not the powerline frequency. The size and weight of converters, on the other hand, depend on the switching frequency of the converter, not the powerline frequency. The converter switching frequency is determined by the state of the technology at the time of design. Presently, transistor converters operate in the range of 15–100 kHz and thyristor converters operate in the 5–15 kHz range. Isolation between ac input power and the dc output filter is accomplished with transformers that are designed for the switching frequency. The size and weight of the magnetics and filters depend on this switching frequency, not the powerline frequency.

The output emi filter is designed to attenuate the high frequencies generated by the switching elements in the circuit, and its size and weight are independent of powerline frequency.

The circuit layout and packaging, combined with the input and output emi filters, keep the circuit from radiating or conducting high frequency emi to other circuits.

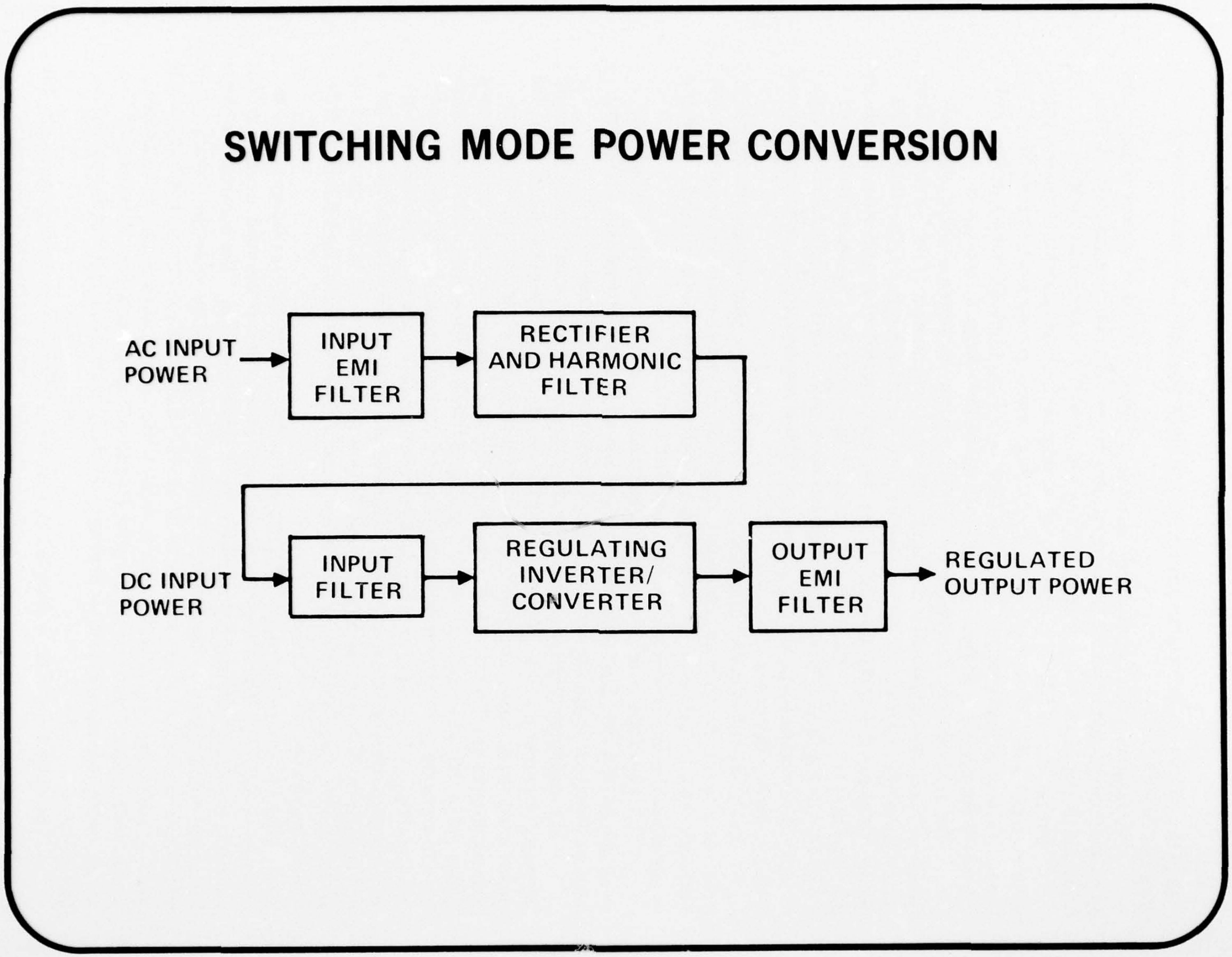
SWITCHING MODE POWER CONVERSION
AC INPUT POWER
INPUT EMI FILTER
RECTIFIER AND HARMONIC FILTER
DC INPUT POWER
INPUT FILTER
REGULATING INVERTER/ CONVERTER
OUTPUT EMI FILTER
REGULATED OUTPUT POWER

Figure 22.

The only component in the system whose size and weight depend on powerline frequency is the harmonic filter. If harmonic current suppression to protect the power source is not required, switching regulator size and weight depend only on output power and technology, rather than on whether the unit is designed for 60- or 400-Hz use.

ADVANTAGES

Switching mode converters have substantial advantages over their dissipative counterparts described under Power Supply Technology. Since the dissipative regulator is widely used and understood, it will be used as the baseline to which the switching mode converter is related.

A switching regulator is 1/6 to 1/2 as large and 1/6 to 1/3 as heavy as its 60-Hz dissipative counterpart. It is also smaller and lighter than its 400-Hz dissipative counterpart. Its relatively high efficiency – 65-95 percent – means that for a given load power, little additional power is drawn from the platform power source to be dumped as heat into the platform cooling system. Unlike a dissipative regulator, its efficiency remains high over wide variations in input voltage. Because of these significant advantages, switching regulators are being increasingly used, even in shipboard equipments with 400-Hz input power. These advantages are even more significant when the comparisons are made at the system level.

EFFICIENCY – OVER WIDE INPUT VOLTAGE VARIATIONS

Efficiency, η, is defined as the output power divided by the input power and is expressed as a number less than 1.0 or as a percentage when multiplied by 100. Power loss in the circuit is the output power subtracted from the input power. There are no inherent loss mechanisms in the class of switching mode converters being discussed. Given ideal (lossless) components, switching mode converters would be 100 percent efficient. This is not true of dissipative regulators, where a power loss mechanism is used to obtain regulation.

Calculation of efficiency is a well developed discipline in the design of power conversion circuitry, where the loss of each component in the design is calculated and/or measured. The major losses in converters are due to the finite voltage drops across conducting semiconductors, I^2R losses in conductors (including windings in magnetic components), hysteresis losses in magnetic materials, eddy current losses, switching losses, losses in control, drive, and housekeeping circuits, and losses in emi suppression circuits. (Emi energy will propagate from the circuit unless it is converted to heat or recovered in a useful form.)

The simplified empirical equation η = output voltage/(output voltage + loss voltage) can be used to estimate the efficiency of converters with output voltages of less than 28 V dc. With 2 volts as a good estimate for the loss voltage, this equation gives an efficiency of 71 percent for a 5 V regulator and 88 percent for a 15 V regulator. If the loss voltage is more than 3 volts, (η = 62 percent for 5 V output and 83 percent for 15 V output) efficiency was probably not an important design factor or was preempted by more important considerations at the cost of efficiency. A loss voltage of one volt (η = 83 percent for 5 V output and 93 percent for 15 V output) would indicate a very fortunate design or the sacrifice for high efficiency of some design factor such as emi control. There is a tradeoff between efficiency and size or weight in converters; over a limited range, efficiency can be increased at the sacrifice of size or weight.

An important feature of switching mode converters which is not true of dissipative regulators is that the efficiency is independent of the tolerance of the input power. A

dissipative regulator with a 5 V output designed to operate through the 18 percent transient of Type I ship service power would be 46 percent efficient at the high line steady-state input. A comparable switching mode circuit would be 71 percent efficient, and its efficiency remains high over wide variations in input voltage.

The increased efficiency means that less power is drawn from the power source, less heat is dumped into the cooling system, and the size and weight of heat exchangers are reduced. Thus the size of both the power conversion equipment and the system it is used in is reduced. High efficiency can also increase reliability since the generation of less heat results in a smaller temperature rise for a fixed heat transfer path.

HIGH FREQUENCY OPERATION

The size and weight of power conversion equipment depend on frequency. Conventional transformer and inductor weight varies inversely as the three-fourths power of frequency if flux density, current density, and other design parameters are kept constant. Capacitor impedance and consequent weight for a given impedance vary inversely with frequency. Semiconductor switching losses, magnetic hysteresis losses, eddy current losses, skin effect conduction losses, and the like also depend on frequency. When frequency is available as a design parameter, tradeoffs between cost, size or weight, and efficiency are possible. These tradeoffs have progressed to the point that computer programs are available that either will optimize efficiency, given a weight constraint, or will optimize weight, given an efficiency constraint.[33] When power conversion is tied to the powerline frequency, this tradeoff is not available. The frequency at which an optimum efficiency or weight design occurs varies with the state of the art of power conversion technology and is presently in the range of 5–50 kHz and moving higher as technology progresses. These frequencies are well above the available shipboard powerline frequencies of 60 Hz and 400 Hz. The result is that even when 400-Hz power is available, higher-frequency converter technology is used to make the power conversion equipment smaller and lighter. These converters will accept dc, 60-Hz, and 400-Hz input power.

Besides size and weight, cost is also a factor that favors going to higher frequencies. Semiconductor technology, both in power semiconductors and complex integrated circuit controls, makes high frequency operation possible. The cost of this technology has continually decreased and is expected to continue decreasing. At the same time, the cost of magnetic core materials and copper conductor is increasing. The amount of copper and magnetic core material decreases with frequency. Less packaging is required and less heat sink material is also required due to the high efficiency of switching mode converters. The result of these reduced material costs is that high power switching mode converters are less expensive than their dissipative counterparts. The power level where the crossover occurs is becoming less and less.

A regulator cost formula that can be used to compare the cost of switching regulators and dissipative regulators is as follows:

$$\text{Cost} = \left(\text{basic cost} + \frac{\text{cost}}{\text{watt output}} + \frac{\text{cost}}{\text{watt loss}}\right)\left(\frac{\text{watt loss}}{\text{watt output}}\right) .$$

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[33] Yu, Y, Backmann, M, Lee, FCY and Triner, JE, Formulation of a Methodology for Power Circuit Design Optimization, paper presented at IEEE Power Electronics Specialists Conference, Cleveland, Ohio, 8–10 June 1976

Switching regulators are more complex to design and, due to emi, more complex to package than dissipative regulators. This is reflected in the basic cost factor. The cost increase as the output power increases is due to two factors. The first is related to the throughput power. Size and weight of transformers and filters increase as output power increases. The second is related to increased power losses in the regulator as output power increases. The added losses require larger heat sinks, more power semiconductors, and increased packaging volume.

An example of the formula applied to dissipative and switching regulators is shown in figure 23, which uses values from Table 2.

The crossover in cost occurs between 500 and 600 watts, which is about correct for 1976 technology.

Frequency of operation of the switching regulator affects efficiency and the cost of the transformers, filters, and switching mode power transistors. The location of the crossover point is a function of the basic cost and the slope of the curve of cost vs watts of output. The latter is strongly affected by the size of the transformers and filters, the efficiency of the regulators, and the relative cost of switching mode power transistors and conventional power transistors. The trend is for the crossover point to occur at lower output power as technology improves.

Another attribute of high-frequency operation is decreased audio noise. The change from 60-Hz power to 400-Hz power places the audio noise generated from power conversion equipment in an annoying portion of the audio spectrum. The frequency of switching mode converters is often selected in the 20-kHz region, even if the electrical optimum is lower, in order to place audio noise beyond the upper limit of human hearing.

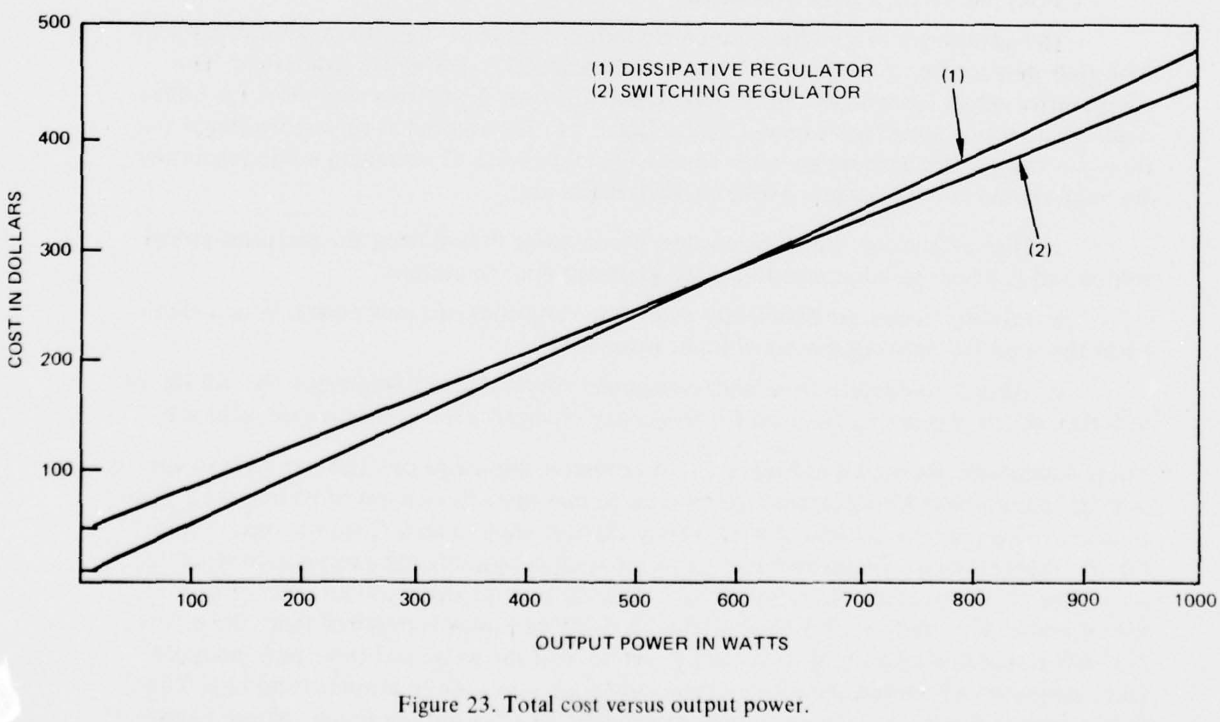


Figure 23. Total cost versus output power.

Figure 23.

TABLE 2. COST COMPARISONS OF SWITCHING AND DISSIPATIVE REGULATORS.

Type Regulator	Dissipative	Switching
Basic Cost	$10.00	$50.00
Cost/Watt of Output	$0.20	$0.20
Efficiency, %	46	71
Watt Loss/Watt of Output, %	54	29
Cost/Watt of Loss		
Heat Sink	$0.10	$0.10
Packaging	$0.20	$0.20
Transistor	$0.20	$0.50
Total	$0.50	$0.50
10 W Output Total Cost	$10.00	$50.00
1000 W		
Cost/Watt of Output	$198	$198
Cost/Watt of Loss	$270	$203
Total Cost	$478	$451

SYSTEM LEVEL ADVANTAGES

The advantages of switching mode regulators over their dissipative counterparts are such that they are being used as one-to-one replacement for dissipative regulators. The comparative advantages of switching mode regulators over dissipative regulators for 60-Hz single-phase input power are summarized in figure 24. Substantial as these advantages are, there are still greater advantages when certain characteristics of switching mode regulators are exploited in system design. These characteristics are:

a. High efficiency, which means less power to be drawn from the platform power source and less heat to be dumped into the platform cooling system.

b. Ability to operate efficiently over wide variations of input power, which eliminates the need for tight regulation of input power.

c. Ability to operate from platform power sources of any frequency (dc, 60 Hz, or 400 Hz), which eliminates the need for frequency changers such as motor-generator sets.

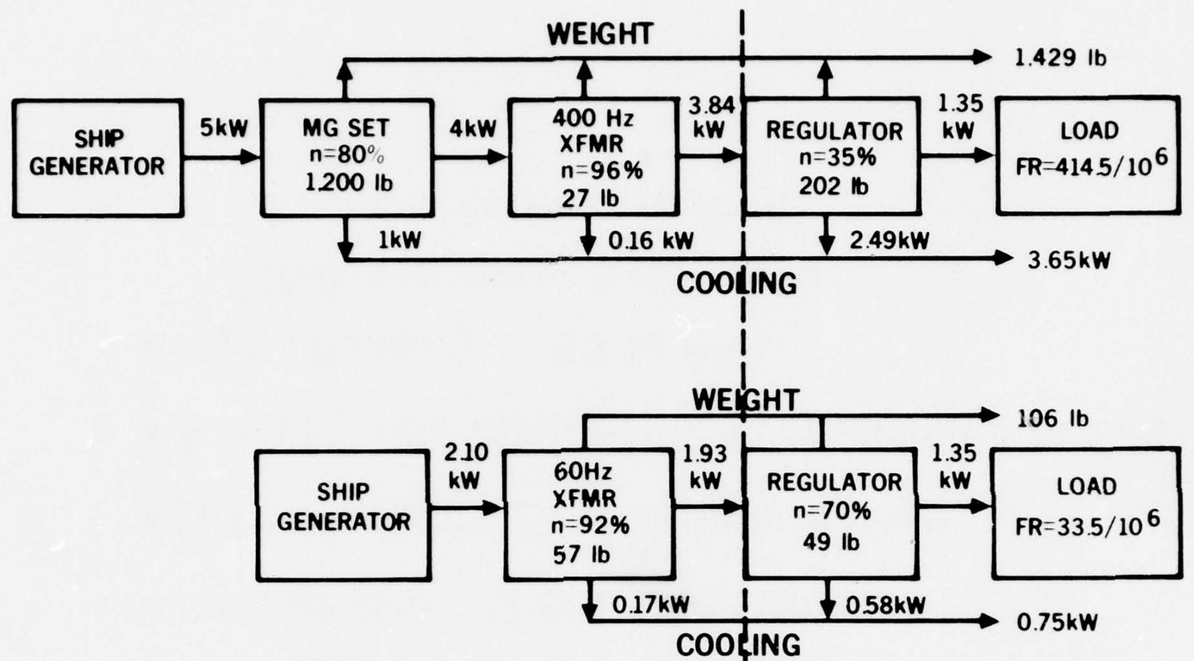
These advantages are shown in Figure 25. A common shipboard practice has been to specify 400-Hz input power for electronic equipment to minimize the weight of its magnetic components. This requires the use of a frequency changer such as an MG set to convert from 60- to 400-Hz power. Dissipative regulators are then commonly used to provide regulated power for the electronics. The upper block diagram reflects this configuration. For 1.35 kW of power delivered to a 5-V dc digital load, 5 kW of power is required from the source, 3.35 kW is dumped into the ship's cooling system, and the weight of this "power supply" (the components between the load and the power source) is 1429 pounds (650 kg). The failure rate of this type of power supply is typically 414 per million hours. These figures are

ADVANTAGES OF SWITCHING REGULATORS

- Smaller size (2 to 6 times smaller)
- Lighter weight (3 to 6 times lighter)
- Accepts wide input voltage variation (up to 10:1)
- High efficiency (65 to 95%)
  - Reduced power from source
  - Reduced cooling required

Figure 24.

SYSTEM IMPACT OF SWITCHING REGULATORS - SHIPS



Improvement

• WEIGHT	13.5
• POWER FROM SOURCE	2.4
• POWER INTO COOLING SYSTEM	4.9
• RELIABILITY	12.4

← ELECTRONIC/ELECTRICAL SYSTEM INTERFACE

Figure 25.

based on data shown for standard military specification power supplies from a vendor's catalog.[34]

Using military specification switching regulator power supplies from the same vendor's catalog, the need for a frequency changer is eliminated and the results are shown in the lower block diagram. For the same 1.35-kW load, power required from the source is only 2.1 kW, power dumped into the cooling system is only 0.75 kW, the weight of the power supply is only 106 pounds (48 kg), and the failure rate is only 33.5 per million hours. Compared with the newer switching regulators, the standard power system is 13.5 times heavier, draws 2.4 times more power from the source, dumps 4.9 times more power into the cooling system, and has 12.5 times greater failure rate. This study shows the system leverage achieved through the use of switching regulator power supplies. What happens in a specific equipment example?

Figure 26 shows the impact of redesigning the AN/SPG-51 radar to exploit the advantages of switching mode regulator technology. Radar Set AN/SPG-51 is a pulse Doppler tracking radar used for gun and missile fire control. It is part of the TARTAR missile system widely used on US and NATO ships. The contractor has proposed redesigning the pulse transmitter and the CWI transmitter to exploit the advantages of switching regulator technology.

Presently the six-cabinet pulse transmitter operates from 60-Hz power, and its power conditioning equipment is housed in two of those cabinets. Redesigned to use switching regulator technology, the power conditioning equipment can be packaged in the spare space within one transmitter cabinet, eliminating two of the six cabinets heretofore needed. Transmitter weight can thus be reduced by 58 percent, floor space by 30 percent, and power consumption by 12 percent. At the same time, its reliability will increase by 40 percent.

The present CWI transmitter requires 400-Hz input power. Through the use of switching regulator technology, the weight can be reduced by 350 pounds (159 kg). But more significantly, since it will then accept 60-Hz power, three MG sets and their controllers, weighing a total of some 11 000 pounds (5 Mg), can be eliminated from the ship's power system.

This example shows that the leverage gained in system figures of merit through the use of switching regulators is proving true in redesigns of actual equipment.

(A telecon from NSEA 6542F on 20 September 1976 reported the current status of the AN/SPG-51 potential changes: Redesign of the CWI has been approved. Redesign of only the power supply portion of the pulse transmitter is being considered, which will not result in as much improvement as could be obtained.)

LOAD ADVANTAGES

Electronics technology tends toward the increasing use of digital processing and control techniques. And in digital processing, the use of memory elements is increasing. As an example, system equipment interconnections are being designed as serial data transmission lines, which provide lower cabling weight and complexity and permit greater functional redundancy. The required parallel-to-serial conversion for serial data transmission requires memory elements, but digital systems with memory are very sensitive to transient power losses. For these systems, recovery software and hardware must be used to correct errors and to preserve and reconstruct memory.

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[34] ACDC Electronics Catalog 371R, ACDC Electronics Inc, Oceanside CA 92504

AN/SPG-51 RADAR

PULSE TRANSMITTER	PRESENT	PROPOSED	IMPROVEMENT
CABINETS	6	4	2
Weight (lbs)	11,220	4,680	6,540
Space (ft^2)	68.3	48.0	20.3
Power (kW)	52.9	47.0	5.9
MTBF (hrs)			40%

CWI TRANSMITTER

- Slightly lighter
- 60 Hz operation
- mg set eliminated

Figure 26.

Switching regulators, because of their energy storage elements and ability to operate over a wide range of input voltage, provide transientfree output power in spite of input transients that would propagate through dissipative regulators. The higher output ripple of switching regulators is well tolerated by both bipolar and MOS digital circuits.

Figure 27 summarizes the system impact of switching regulators on digital type loads.

SYSTEM IMPACT OF SWITCHING REGULATORS - LOADS

Increasing Use of Digital Processing with Memory Elements

- Transient loss of power requires recovery software to
    - Correct errors
    - Reconstruct memory
- System can tolerate higher noise level
    - Error propagation differs from analog systems
    - Components specified for noise rejection
    - Load induced noise quite high
    - Clocked operation

Switching regulators match new load

- Operate over wide range of input voltages
- Higher output ripple tolerated by load

Figure 27.

PRODUCT LINE TREND

That switching regulators are advantageous in systems is reflected by their appearance in more and more company product lines (fig 28).

In an early military application, switching regulators were used in the power supplies for the Army FADAC computer, which had germanium power transistors in a pulse-width modulated regulator operating at 1.2 kHz.

In 1965 the Navy sponsored the development of the MIL-P-81279 power supplies, a family of 20-kHz switching regulators and dissipative regulators designed for operation from aircraft 400-Hz power. These power supplies are still being produced and sold.

In 1966–1967, low-cost power transistors capable of switching at 20 kHz became available, and switching regulators were introduced into the commercial power supply market as a standard item. In 1972–1973 a survey of the major power supply vendors that included all those with annual sales over $2 million indicated that all but three either had a standard switching regulator product line or planned to have one by the end of 1973. A 1974 market survey[35] found 1000 to 1400 companies in some phase of manufacturing power supplies, 200 to 300 of them selling to noncaptive markets. Today (1976) most power supply manufacturers probably have switching regulator power supplies available in their product lines.

REPRESENTATIVE MODELS

In 1972, one representative model was purchased from every power supply vendor who had as a standard item a switching regulator that either was frequency independent or could be easily modified to be frequency independent. They are shown in figure 29. The purchase orders totaled less than $12 000. In 1976, the models of all available switching regulators with circuit configurations that could be made frequency independent had increased more than tenfold. Switching regulators are available in today's market because their advantages created a demand and because they can be manufactured at prices competitive with dissipative regulator prices.

Most of the switching regulators used in Navy equipment are either militarized standard designs or custom designs. Characteristics of several switching regulators being used in the Navy will be discussed. Of interest is their wide range of electrical output capabilities – from a few watts to 300 kilowatts in a single unit, and from a few volts to several kilovolts.

STANDARD ELECTRONIC MODULE PROGRAM

The Navy Standard Electronic Module (SEM) R&D program is aimed at developing a standard family of power supplies that can be used with SEM and other modules in aircraft and shipboard applications. Because of the size and weight restrictions on aircraft, the aircraft requirements have predominated in the configuration selection. As presently conceived (starting FY 77), the basic power supply (fig 30) is a switching regulator dc-to-dc converter that accepts either 3-phase 400-Hz 115/200-V ac power or 270-V dc power, as defined by MIL-STD-704B. (270 V dc is obtained when 115/200-V ac power is rectified.) Output voltages are pin-programmable 5/5.2-V dc, 12/15-V dc, or 25/28-V dc in various power ranges from 50 to 360 W. Since +5 V is required in most systems, small auxiliary

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[35] Frost and Sullivan Inc, 106 Fulton St, New York NY 10038, The Power Supply Market, December 1974

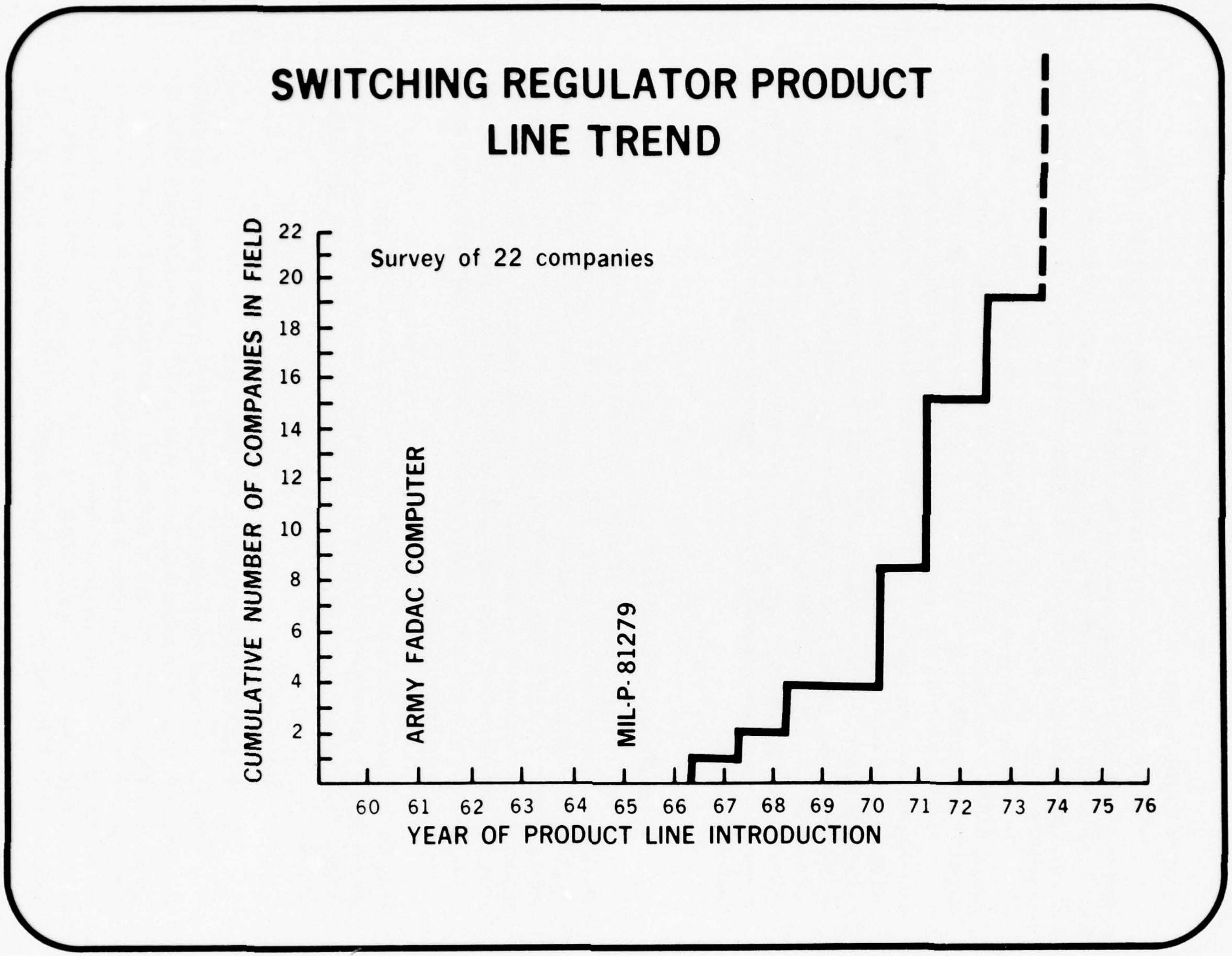
SWITCHING REGULATOR PRODUCT LINE TREND
Survey of 22 companies
ARMY FADAC COMPUTER
MIL-P-81279
CUMULATIVE NUMBER OF COMPANIES IN FIELD
2 4 6 8 10 12 14 16 18 20 22
60 61 62 63 64 65 66 67 68 69 70 71 72 73 74 75 76
YEAR OF PRODUCT LINE INTRODUCTION

Figure 28.

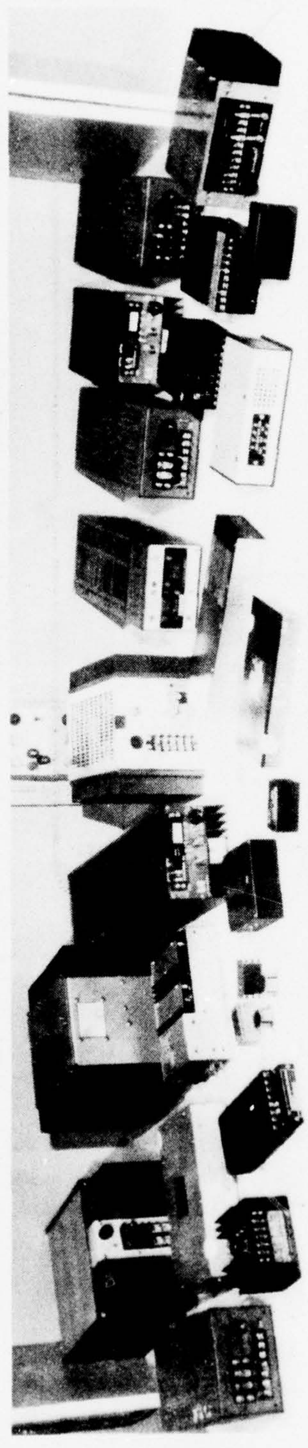

Figure 29.

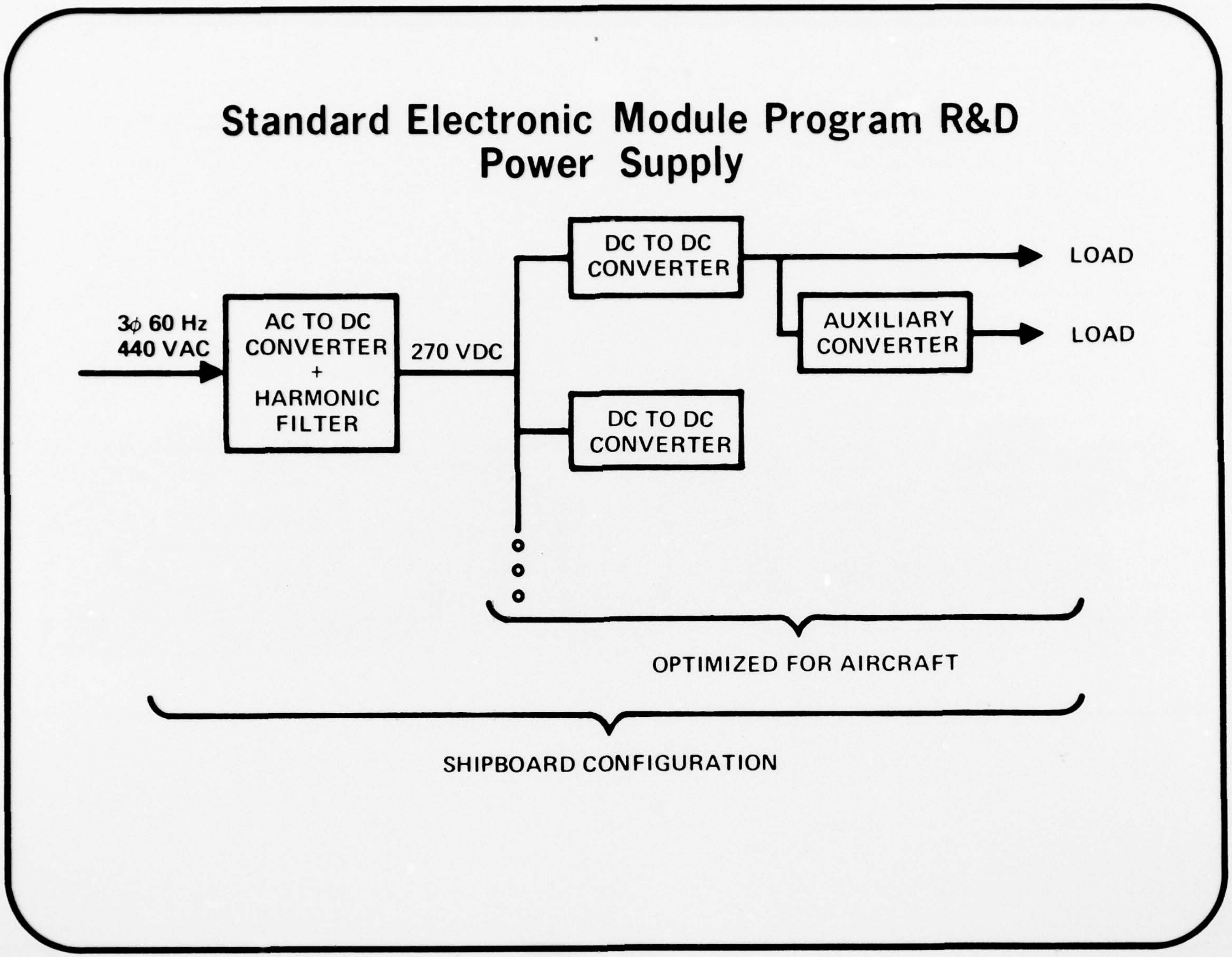
Standard Electronic Module Program R&D Power Supply
3φ 60 Hz
440 VAC
AC TO DC CONVERTER + HARMONIC FILTER
270 VDC
DC TO DC CONVERTER
DC TO DC CONVERTER
AUXILIARY CONVERTER
LOAD
LOAD
OPTIMIZED FOR AIRCRAFT
SHIPBOARD CONFIGURATION

Figure 30.

converters (5 W, 15 W, 25 W) are available to furnish ±5, ±15, and ±25 V dc from a 5-V source provided by a basic converter.

The basic dc-to-dc converter is not compatible with shipboard power sources either in harmonic currents drawn or in voltage level. Therefore, a shipboard converter is added that accepts 3-phase 60-Hz shipboard power and converts it to the 270 V dc accepted by the basic converter. The shipboard converter also contains the harmonic filters necessary to attenuate rectification harmonics to acceptable levels. The shipboard converter consists of a transformer-rectifier set and the harmonic current filter or solid-state equivalent. Only one shipboard converter is required per cabinet or subsystem.

None of the present approaches to reducing harmonic currents are considered fully satisfactory. Keeping the harmonic filters as separate units allows improvements in filter technology to be incorporated into a system with no impact on the basic power supplies or the rest of the system. Harmonic current reduction is an important technical consideration in shipboard electronic equipment design and will be discussed further.

OTHER NAVY APPLICATIONS

MIL-P-81279 SWITCHING REGULATOR POWER SUPPLIES[36]

This family of power supplies was developed by the Navy for avionic applications. Since the original development in 1965, the family has been used for Air Force, Navy, Army, and commercial applications. The family contains both dissipative and switching regulator members. The switching regulators, as shown in figure 31, range in output power from 7.5 to 60 watts. A 400-Hz transformer at the input restricts the operation to 400-Hz sources, although larger 60-Hz commercial versions are available.

AEGIS SWITCHING REGULATOR POWER SUPPLIES[37]

A family of standard switching regulator power supplies was developed for the AEGIS AN/SPY-1 radar signal processor (fig 32). Input power is 3-phase 115-V 400-Hz Type I power per MIL-STD-1399, Sec 103. However, the basic circuit (less emi filter and circuit breaker) will operate from dc, 50-Hz, 60-Hz, and single-phase power. Output power of a single unit ranges from 100 to 300 watts. Up to four units can be used in parallel for 1200 W output. Special characteristics include redundancy features that provide uninterrupted bus power in the event of a power supply failure.

AN/BQQ-5 AND AN/BQQ-6 SWITCHING REGULATOR POWER SUPPLIES[38]

A family of switching regulator power supplies was developed for the AN/BQQ-5 and AN/BQQ-6 sonar equipments (fig 33). Input power is ship service 3-phase 115-V 60-Hz power. However, the basic circuitry concept is frequency independent, and slight modifications allow operation from standard aircraft and shipboard ac power sources or from dc

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[36]Department of the Navy Military Specification MIL-P81279 (WP), Power Supply, Miniature, General Specification for, 1 August 1965, Supplement 1A, 1 May 1968, MIL-P-81279/1 through /6, 1 August 1965, and /7 through /12, 1 May 1968

[37]RCA Dwg 49671-8144430, General Specification for Low Voltage Power Supplies, 16 March 1972

[38]IBM Bulletin 76-67H-001, Modular Power Supply, March 1976

MIL-P-81279 SWITCHING REGULATORS

INPUT POWER: 3ϕ 115 V/200 V 400 Hz

Slash Sheet	Voltage	Current	Power
	V	A	W
2	3	5	15
4	6	5	30
6	12	5	60
7*	1.5 – 6	5	7.5 – 30
8*	3	5	15
9*	6	5	30
10*	6	15	90
11*	12	5	60
12**	28 and 28	2.5	60 and 60

* Requires power module for input
** Power module: 3ϕ 115 V/200 V 400 Hz to 28 Vdc

Figure 31.

AEGIS AN/SPY-1 RADAR LOW-VOLTAGE POWER SUPPLIES

	Output			
Model	Voltage	Current	Power	Size and Weight
	V	A	W	
900	5	60	300	A
901	5	25	125	B
902 Dual	5 and 5	10 and 10	50 and 50	B
902	10	10	100	B
903 Dual	5 and 12	10 and 10	50 and 120	B
903	18	10	180	B
904	25	10	250	B

	Size	Weight
A	17″ x 4.54″ x 5.22″	16 lb
B	8.5″ x 4.54″ x 5.22″	8 lb

Input power
3ϕ, 115 V, 400 Hz

Figure 32.

AN/BQQ-5 AND AN/BQQ-6 SONAR POWER SUPPLIES

- 14 TYPES
- 5 TO 90 V VOLTAGE RANGE
- 0.1 TO 70 A CURRENT RANGE
- SINGLE OUTPUT POWER TO 350 W
- INPUT POWER: 3ϕ, 115 V, 60 Hz

Figure 33.

voltages obtained by rectification of those power sources. Single-unit power supplies have multiple output voltages with single output powers up to 350 watts. The power supplies are packaged in a configuration compatible with the Navy Standard Electronic Module (SEM) program modules. The basic circuit is used on several Navy, Air Force, Army, and NASA equipments.

LINE-INDEPENDENT SWITCHING REGULATOR POWER SUPPLIES

This family of switching regulator power supplies is based on standard 10-kHz SCR power conversion modules (fig 34). A basic module operates from dc power obtained from rectified 115-V 60-Hz or 400-Hz ac power. The module inputs can be placed in series to operate from a 440-V ac source. The basic power level is 7 kW, but units can be paralleled to provide any desired output power. Output voltages can be as high as 50 kV. The module has been used in Navy and Army equipments and is the basis of the Navy AN/SPG-51 redesign.*,**

MARK 84 FREQUENCY CHANGER[38]

This equipment is used to convert 60-Hz shipboard power to 400-Hz input for the AEGIS system on USS NORTON SOUND (fig 35). The output power is ac rather than the dc output of the previous examples. The conversion approach, however, is first to rectify input power to dc power and then to perform power conversion at frequencies independent of the input line frequency. The output power is 400 Hz, but the output could be designed to provide any frequency including dc. The output power of this unit is 300 kW.

*NELC Trip Report, Line Independent Power Supply (LIPS) meeting, by J Foutz, 10 February 1975
**Telecon between J Foutz, NOSC 7434, and M Foster, NSEA 6542F, on 20 September 1976

LINE-INDEPENDENT POWER SUPPLIES (LIPS)

(AN/SPG-51 RADAR)

- 7-kW MODULES PARALLELABLE TO ANY POWER
- OUTPUT VOLTAGES TO 50 kV
- FREQUENCY-INDEPENDENT INPUT
  - 3ϕ
  - 115 V OR 440 V
  - 60 Hz OR 400 Hz
- SCR POWER SWITCHES
- 10 kHz SWITCHING FREQUENCY

Figure 34.

AEGIS MARK 84 SOLID-STATE FREQUENCY CHANGER

- INPUT : 3ϕ, 440 V, 60 Hz
- OUTPUT: 3ϕ, 440 V, 400 Hz, 300 kW
- SWITCHING PEGULATOR DESIGN USING POWER TRANSISTOR
- TECHNIQUE APPLICABLE TO DC OUTPUT VOLTAGES

Figure 35.

AVAILABILITY OF TECHNOLOGY

Switching regulators are nonlinear, discrete time, multiloop, multi-input feedback circuits having components with wide parameter variations. The components work at high stress levels. Early designs were made mostly by trial and error and by modification of previous designs. Systematic analysis and design techniques either did not exist or were unknown to the designers. That situation is rapidly changing and a strong technological capability is developing (see fig 36).

Power electronics courses covering the design principles of switching regulators are now taught in many universities, usually at the graduate level. These universities include Duke University, California Institute of Technology, University of Missouri, Purdue, University of Toledo, University of Toronto, Canada, and the Delft Institute of Technology, The Netherlands. Other universities are in the process of expanding into the power electronics area.

The aerospace industry has been the major user of switching regulator power supplies until recently, either designing them themselves or having them designed by custom power supply vendors. Aerospace cutbacks stimulated the flow of experienced design engineers into the engineering staffs of commercial power supply vendors.

NASA has a substantial in-house capability in power electronics, but in-house capability in DoD is limited.

In order to better exchange technical information in the field, the IEEE Aerospace and Electronics Group established the Power Electronics Specialists Conference (PESC) in 1970. That group meets annually and publishes proceedings. Over 300 specialists attend the conference each year. POWER CON, a commercially sponsored conference, was established in 1975 and meets twice a year. The organization sponsoring POWER CON also publishes a bimonthly trade magazine in the field titled Solid State Power Conversion.

The Interagency Advanced Power Group (IAPG) was established in 1960 by various federal agencies to exchange technical information. Power electronics is within its field of interest and pertinent working groups meet annually. Members include representatives from the Army, Navy, Air Force, National Aeronautics and Space Administration, National Science Foundation, Energy Research and Development Administration, Department of Defense, Department of Transportation, and Department of Health, Education and Welfare.

Most of the published information on switching regulator design is in the form of articles in technical journals or in vendor literature. Information in book form is limited. To make up for the lack of information available in book form, NASA has sponsored the development of a 600-page Power Electronics Design Guide that will be available within a year.

Through the mechanisms discussed here, power electronics technology is being made generally available to the engineering community.

More and more switching regulators are going to be used in Navy electronic equipment because

They have inherent advantages in size, weight, and efficiency.

They have a large beneficial impact on system figures of merit when their characteristics are properly applied in system design.

They are becoming better understood and increasingly available as systems components.

Availability of Technology

- Universities
- Aerospace industry
- Custom power supply vendors
- Commercial power supply vendors
- NASA
- DoD
- Conferences
- Literature

Figure 36.

POTENTIAL PROBLEMS

Do switching regulators have any characteristics that could cause system problems? The answer is yes. However, for each characteristic that is a potential problem there is a design approach to avoid the problem. System designers must understand switching regulator characteristics if they are to fully realize their advantages while avoiding their potential problem areas. Figure 37 lists some of the problem areas and their solutions.

FILTER EFFECTS

If full-load or short-circuit current has been established in the inductor in the low-pass filter of a series switching regulator and the load is suddenly removed, the best the regulator can do is to open the modulation switch in the switching regulator (fig 38). All the energy stored in the inductor (I^2 $L/2$) ends up as energy stored in the capacitor (V^2 $C/2$), and a voltage overshoot occurs. The overshoot voltage is the vector sum of the nominal output voltage and a voltage equal to the change in current times the characteristic impedance ($Z_O = \sqrt{L/C}$) of the output filter. For a fixed LC ratio (characteristic impedance), the percentage overshoot is greatest for low-voltage supplies such as 5-V logic supplies. Economic tradeoffs often favor a large L and a small C. The overshoot resulting from a sudden load removal or the clearing of a short circuit can destroy bipolar logic circuits. Undershoot, transient response, and ripple are also affected by the selection of the LC values in the output filter circuit.

The engineering solution to these problems is to carefully select the proper values of LC. This has not always been done in the past. Unfortunately, some of the popular application notes that serve as models for design have improperly selected values of LC. External overvoltage protection circuits are often used to protect against catastrophic overshoots. The preferred solution is proper selection of LC values in the filter section, with added circuitry to protect the device from catastrophic voltage overshoots that can occur under abnormal conditions.

CONSTANT POWER INPUT

For a given output power, the input power of a switching regulator is constant. The input characteristic of a switching regulator is therefore a power hyperbola, and the input current decreases as the input voltage increases (fig 39). This behavior is opposite that of a resistive load, where input current increases as input voltage increases. The incremental input resistance ΔR, is a negative resistance:

$$\begin{aligned}\Delta R &= dV/dI \\ &= d(P/I)/dI \\ &= -P/I^2 \\ &= -V/I \\ &= -R\,.\end{aligned}$$

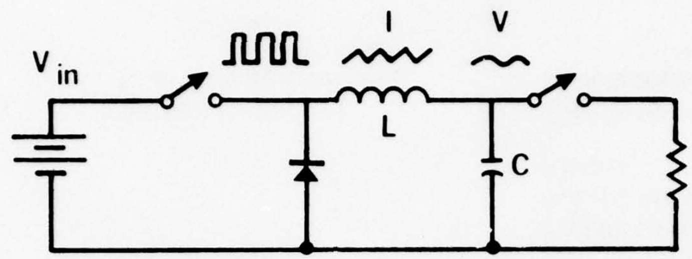
Because of this negative input impedance characteristic, a switching regulator (or any high-efficiency power conversion system) can be turned into a power oscillator by adding to the input passive LC components such as interconnecting cables or emi filters. The engineering solution for passive components has been completely defined in Navy-sponsored work

Potential Problems With Switching Regulators

Characteristic	System impact	Solution
• **Filter effects** Over shoot Under shoot Transient response *Ripple*	Out-of-specification Voltages	Proper LC ratio Proper circuit configuration
• **Constant power** Input characteristic	System instability Component failure Inability to turn on	Proper interface analysis and control Protection circuit
• **High dI/dT, dV/dT**	EMI problems	Careful layout and packaging Proper component selection Special circuit techniques Filters
• **Stability difficulties**	System instability Degraded performance	Two loop control New analysis techniques

Figure 37.

OVER SHOOT



Prior to switch opening :

- Energy in inductor $= \frac{I^2 L}{2}$
- Energy in capacitor $= \frac{V^2 C}{2}$

After switch opening (final value) :

- All energy stored in capacitor

$$V_f = \frac{2E}{C}$$
$$= \left(V_i^2 + \frac{I^2 L}{C}\right)^{1/2}$$

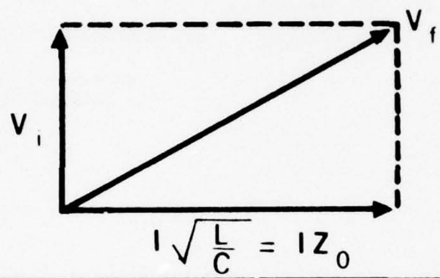
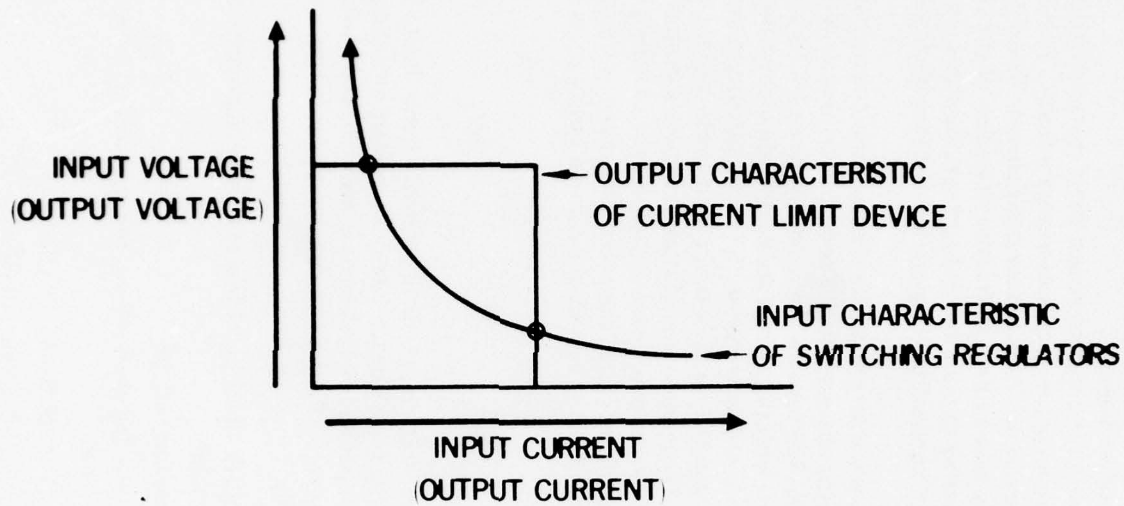


Figure 38.

CONSTANT POWER INPUT



- Negative input resistance can cause power system instabilities
- Regulator can be destroyed by low input voltage
- Undesirable stable mode when operated from current limited source

Figure 39.

completed in 1976 and reported in MIL-HDBK-241[39] and an IEEE paper.[20] The negative input resistance can also affect other feedback systems such as ship service generators, MG sets, and solid-state frequency changers. This is a more complex situation, and a completely defined engineering approach must still be found.

Another potential problem with the constant power input characteristic is that as the input voltage goes to zero, the input current increases toward infinity. These high currents at low input voltages can destroy switching regulator components. The engineering solution is to add protective circuitry that inhibits destructive operation of the switching regulator at low voltages. It is interesting to note that military specifications require survival of electronic equipment through high-input-voltage regions but not through low-input-voltage regions.

A final potential problem occurs with the constant power input characteristic when it is combined with the current limiting characteristic of some power sources and some of the new solid-state power controllers. The turn-on trajectory of the switching regulator starts at low voltage and high current, with the desired stable operating point being the desired input voltage. If the trajectory wants to start in the region of current limitation, an undesirable stable operating point is reached on the current limit curve, and the desired operating point cannot be reached. The engineering solution is to have a protective circuit that inhibits low-voltage operation. The turn-on characteristics of the switching regulator must be closely coordinated with the current limit characteristics of any current-limited power source or solid-state power controller to be sure the turn-on trajectory is inside the current limit region.

EMI

Switching regulators generate electromagnetic interference (emi) due to high rates of change of current and voltage in the switching circuitry. To prevent switching regulator units from causing emi, filtering all input and output leads is essential, and packaging in an attenuating enclosure is usually necessary. Recent low-emi designs have used a variety of emi suppression techniques including:

- Control of transistor rise and fall times by adding external components rather than relying on inherent characteristics
- Use of soft recovery (but very fast) diodes
- Routing of all switched currents and their returns through twisted pairs or in mirror-image conductors on circuit cards
- Capacitive isolation of high dV/dt points in the circuit
- Use of lossy ferrites in balun and other line inductors
- Use of lossy Mylar dielectrics (rather than the conventional ceramic or mica dielectrics) in high-frequency filter capacitors[40]

By means of these techniques, open-frame power supplies can be made that radiate less emi than enclosed designs of the recent past.

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[39] Department of Defense Military Standardization Handbook, MIL-HDBK-241, 1976

[40] Bloom, SD and Massey, RP (Bell Laboratories), Emission Standards and Design Techniques for EMI Control of Multiple DC-DC Converter Systems, paper presented at IEEE Power Electronics Specialists Conference, Cleveland, Ohio, 10 June 1976

[37] RCA Dwg 49671-8144430, General Specification for Low Voltage Power Supplies, 10 March 1972
[38] IBM Bulletin 76-67H-001, Modular Power Supply, March 1976

Care must be taken that emi control measures effective at the regulator level do not cause system problems. An example of such a problem can be demonstrated by connecting a MIL-P-81279/9 power supply into a system as a negative regulator (fig 40). (There is no problem when it is used as a positive regulator.) In systems having the signal ground and chassis ground tied together at some point, feedthrough capacitors on the input of the switching regulator may act as a capacitive divider that bypasses the regulator and feeds input noise to the load through the chassis. Sneak paths such as this are often difficult to locate and are probably the cause of many system problems caused by power source "glitches." The solution is to find and eliminate the sneak path rather than require a perfect power source.

STABILITY

Switching regulators are nonlinear, discrete time, multifeedback loop, multi-input control systems operating in a high-noise environment. Several of the circuit parameters critical to stability have wide parameter variations. Stabilizing switching regulators has been as much a black art as a science for most designers. One commercial power supply manufacturer stated in 1972 that one out of four new designs attempted had to be abandoned because it could not be satisfactorily stabilized. Several stability characteristics long observed by designers have been analytically described only in the past 3 years (1974–1976). Laboratory techniques to measure open-loop gain/phase in the high-noise switching environment were first described in the open literature in 1975. The way of avoiding these complexities has been either to use extremely conservative stabilizing techniques at a considerable cost in performance or to use marginally stable designs that cause system problems. Engineering solutions to these problems are rapidly being obtained, primarily from NASA-sponsored programs in industry and various universities. Much of the work is reported in Proceedings of the Power Electronics Specialists Conference.

The results of many efforts are being incorporated by NASA into an interactive computer program for the modeling and analysis of power processing systems (MAPPS).[41] NASA has also developed a two-loop standard control module (SCM) that will control all 24 switching regulator circuit configurations.[42] This absolutely stable control system will be the most analyzed and best documented circuit of its type when a handbook on it is completed, in 1977.

[41] TRW Defense and Space Systems Contract NAS-3-19690 for NASA Lewis Research Center, Modeling and Analysis of Power Processing Systems (MAPPS), 20 reports for period April 1975 through November 1976

[42] [illegible], TRW, Stability Analysis and Compensation of a Boost Regulator With Two-Loop Control, paper presented at IEEE Power Electronics Specialists Conference, Murray Hill NJ, 11 June 1974

EMI PROBLEM

- Switching regulators are rich EMI Sources
- Methods of EMI control effective at regulator level can cause system problem.

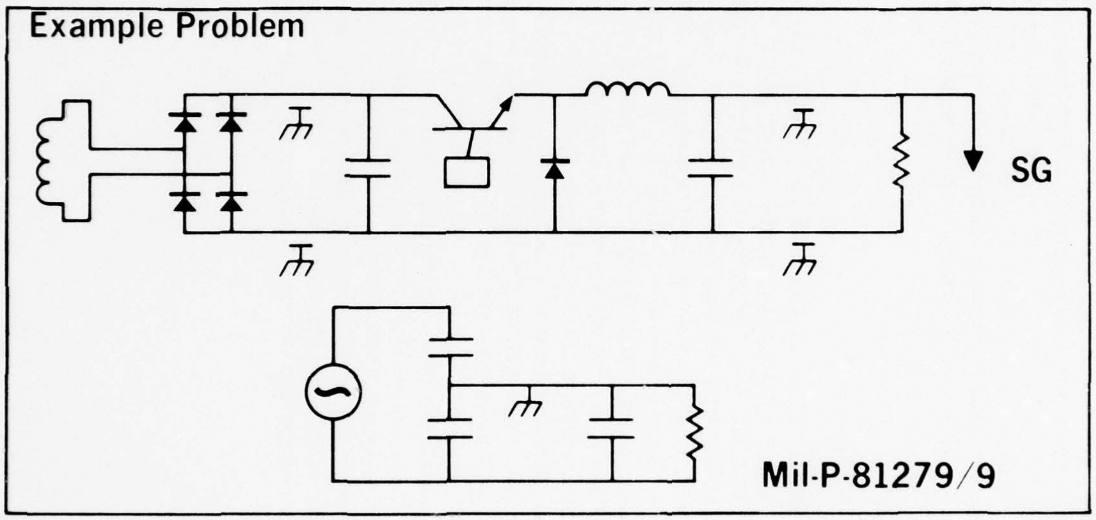


Figure 40.

SUMMARY

In summary, switching regulator technology makes it possible for electronic equipment to be independent of the frequency of the input power source. The design can be identical for any power source – dc, 60-Hz, or 400-Hz. Additional benefits include:

- Small size
- Light weight
- High efficiency (using little power from the source and requiring little cooling)
- The ability to maintain efficiency and performance over a wide range of input voltages
- Low cost and high reliability in high-power-level configurations (the crossover occurring at about 500 W with present technology)

When these advantages are properly understood and realized, substantial system benefits accrue. Switching regulators have special characteristics, however, that must be considered in their design or application. For example, filters must be designed to minimize the effects of overshoot, undershoot, poor transient response, and output ripple; system instabilities caused by the constant power input characteristic must be avoided; protective circuitry must be added internally to the regulator to prevent damage at low input voltages; the interface with current-limited sources must be properly coordinated; and finally, the best design practices available must be used for emi control and for the stabilization of feedback loops. These precautions are easily met by experienced switching regulator designers and users.

Figure 41 summarizes these advantages and precautions.

Summary of Characteristics

Advantages Over Dissipative Regulators

- Frequency independent
- Smaller size
- Lighter weight
- Higher efficiency
  - Reduced power from source
  - Reduced cooling
- Accepts wide input voltage range
- Lower cost and higher reliability in higher power levels

Precautions

- Filter effects
- Constant power input characteristics
- EMI control
- Stability design

Figure 41.

SYSTEM CONSIDERATIONS

FREQUENCY DEPENDENCE OF ELECTROMAGNETIC COMPONENTS

In addition to its power conversion circuitry, shipboard electronic equipment contains other components that are often frequency sensitive – circuit breakers, running time meters, fans, blowers, and other components. What impact do these frequency-sensitive components have on designing for frequency independence?

CIRCUIT BREAKERS

Shipboard circuit breakers identified in the MIL-STD-242F selection standard were studied through literature sources and specifications and by contacting the manufacturers. All circuit breakers studied (fig 42) are frequency sensitive; even with factory modifications, they cannot meet full performance requirements at both 60 and 400 Hz. Theoretically, the performance requirements could be met by developing new electronic versions that would be similar to the new solid-state and hybrid power controllers. An R&D program would be needed to develop and qualify such equipment. In the present circuit breaker specification, the form and fit for both 60- and 400-Hz circuit breakers fortunately are identical for identical current ratings. Thus each electronic equipment, except for the circuit breakers, can be designed without regard for the power frequency, and the appropriate 60- or 400-Hz circuit breaker of current design can be installed to match the power source of the ship.

RUNNING-TIME METERS

MIL-M-3971 covers dc and ac running-time meters (fig 43). The dc version uses an inertia wheel driven by an escapement mechanism similar to that in a watch. While designed for dc, it will operate from ac power between 20 and 200 Hz. At higher frequencies there is insufficient time to wind the meter on a half cycle of power. The mere addition of a rectifier to the meter would make it frequency insensitive. The ac versions use synchronous motors and are frequency sensitive. The 60- and 400-Hz versions have the same form and fit.

As with circuit breakers, present 60- or 400-Hz running-time meters could be installed as required in electronic equipment that is otherwise frequency independent. However, because it would be simple to develop a frequency independent running-time meter, it is recommended that this be done and that the present 60- and 400-Hz versions be used only in the interim.

FANS AND BLOWERS (Fig 44)

Fans and blowers, covered by over 20 military specifications, are all frequency sensitive. Frequency independent designs are possible, however, in either of two circuit configurations. In one, power is rectified to dc, and a dc drive motor is used to power the fan or blower. In the other, a frequency-independent inverter is used to power an ac drive motor. Either approach is more expensive than a conventional ac or dc motor drive.

Alternative cooling methods can eliminate the need for fans and blowers within the electronics. Present specifications assume 60-Hz prime shipboard power and require electronic equipment to use 60-Hz power for fans and blowers even if 400 Hz is used for the electronics. All these approaches are satisfactory. The recommended approach is to let the

Circuit Breakers

Types Considered

• MIL-C-39019	Miniature magnetic	ac or dc	0.05A to 20A
• MIL-C-17361	Thermal-magnetic ABQ and NBQ	ac or dc	10A to 1600A
• MIL-C-17588	Hydraulic-Magnetic	ac or dc	5A to 50A

Conclusions

- All breakers studied are frequency sensitive
- Simple modifications will not make frequency independent
- Frequency independent electronic versions are possible with R&D
- 60 Hz and 400 Hz interchangeable in form and fit

Recommendation

- Use present breakers with 60 Hz or 400 Hz versions as required

Figure 42.

Running Time Meters

Types Considered

MIL-M-3971

SLASH 1	Escapement driven	4–40 Vdc 40–130 Vdc	
SLASH 2	Synchronous motor driven	120 Vac 120 Vac	60 Hz 400 Hz

Conclusions

SLASH 1

- Frequency-independent dc and 20 – 200 Hz
- Minor modification to make totally frequency independent

SLASH 2

- Frequency dependent
- 60 Hz and 400 Hz are form and fit compatible

Recommendation

- Develop frequency-independent running time meter
- Use 60-Hz or 400 Hz versions as required in interim

Figure 43.

Fans and Blowers

Types Considered

Fans and blowers covered by 20 military specifications

Conclusions

- All fans and blowers specified are frequency sensitive
- Frequency independent designs are possible
  - Rectification + dc drive
  - Frequency independent inverter + ac drive
- Alternate cooling methods can eliminate fans and blowers

Recommendations

- Require electronic equipment to
  - Eliminate fans and blowers
  - Use frequency independent fans or blowers
  - Use platform prime power to drive fans or blowers

Figure 44.

manufacturer make the choice, provided the equipment is frequency independent or can be procured to operate from the shipboard prime power source.

LINE FREQUENCY HARMONICS

As noted before, the only frequency-sensitive components in a switching regulator power-conversion system are passive harmonic filters. If conventional passive filtering is used as a method of suppressing harmonics, the line frequency has considerable impact on the size and weight of the filter. However, even a 60-Hz transformer harmonic suppression technique (discussed later) is much more cost effective than the use of frequency changers.

What are the sources of line-frequency harmonics? The main sources are rectifiers and iron-cored transformers. Other current harmonics, sometimes termed "abnormal," can arise from phase unbalances in the supply voltages, asymmetrical firing angles of controlled thyristors, and harmonic voltages in the powerline.

Harmonic currents in a shipboard power system can distort the voltage waveform through the source and distribution system impedances and can decrease the system's power factor. The distorted voltage waveform in turn can cause increased power losses in magnetic devices, reduce the torque of high-efficiency induction motors, cause the excitation of undesirable vibration modes, and cause problems in electronic equipment.

For these reasons, basic specifications such as MIL-E-16400 have been amended to limit harmonic currents to 3 percent or less of the fundamental.[43]

Figure 45 lists the sources of shipboard power system harmonics and the problems associated with them.

RECTIFICATION HARMONICS

Rectification is the primary source of harmonic currents. The maximum harmonic content is related to the ripple factor, which is the number of ripple cycles per fundamental period in the output dc waveform of the rectifier. The harmonic content is independent of the transformer or diode interconnections used.

The case in which $r = 6$ is of interest because it represents the full-wave three-phase bridge rectification configuration currently in wide use in military electronic systems and, significantly, in the new power supply technology. This configuration is used almost exclusively in modern switching regulator power electronics because of its suitability for three-phase direct rectification (with no intermediate transformer) in the conversion to dc power.

The 3 percent specification limit is much tighter than can be met by the $r = 6$ case for an inductive input filter (fig 46), since the lower harmonics (5, 7, 11, 13) require large filters for their attenuation. A potential solution is to go to a higher ripple factor, which will result in a lower harmonic content.

The higher the ripple factor (r), the greater the cancellation of certain harmonics and therefore the lower the total harmonic distortion (THD). Theoretically, only $rm \pm 1$ harmonics are present, where $m = 1, 2, 3, \ldots$. Values of $r = 3, 6, 12$, and 24 are of practical significance. As shown in figure 10, there are no even harmonics for $r = 6, 12$, and 24.

However, in order to use $r = 12$ or $r = 24$ ripple factors, an intermediate transformer is no longer optional but must be used. The higher ripple factors are created by more

[43]Department of the Navy Military Specification MIL-E-16400G, Electronic, Interior Communication and Navigation Equipment, Naval Ship and Shore: General Specification for, Amendment 1, December 1976

Line Frequency Harmonics

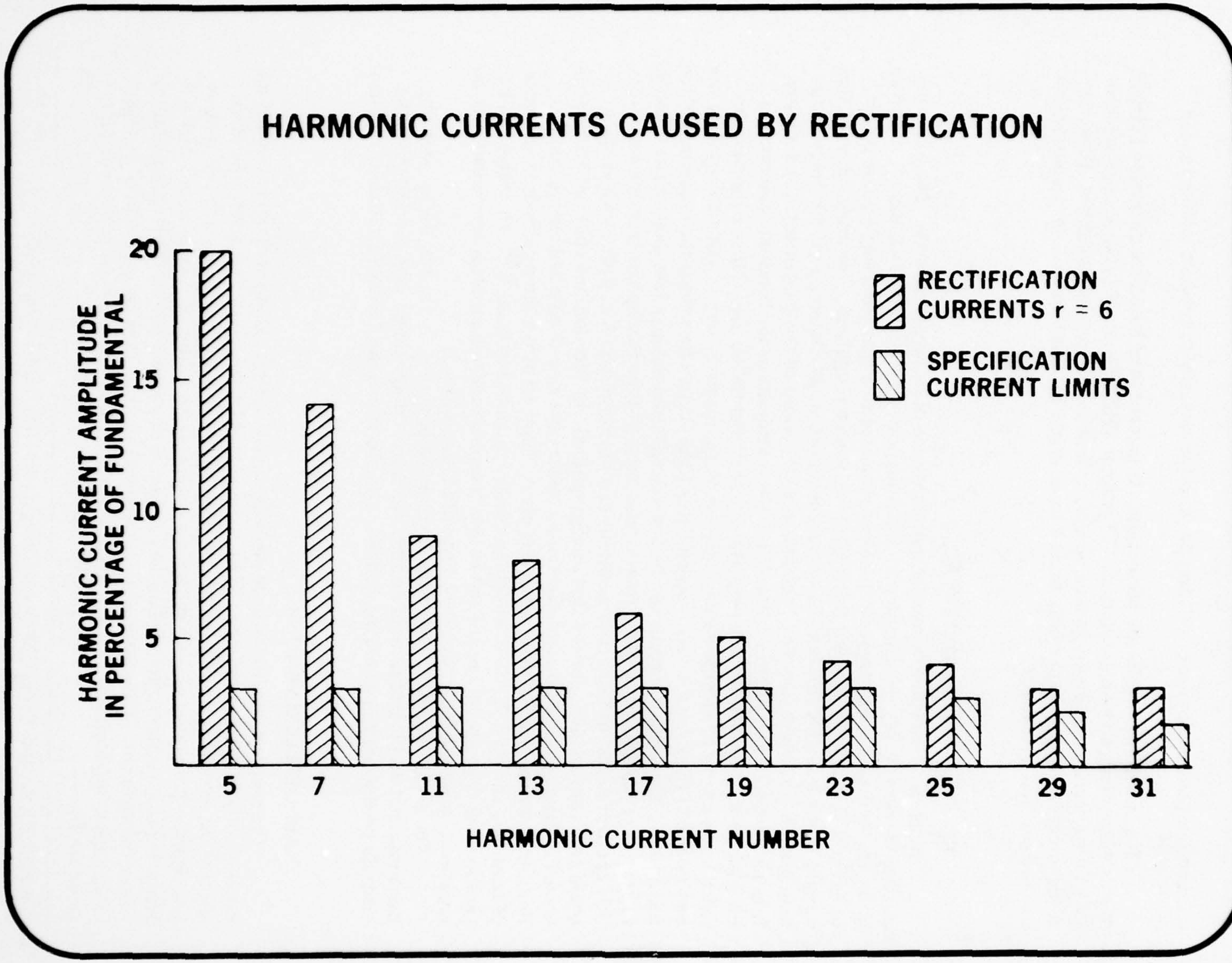
- Generated by power supplies
  - Rectifiers
  - Iron-cored transformers
  - Abnormal harmonics

    Phase unbalances
    Asymmetrical thyristor firing angles

- Problems if excessive harmonics
  - Power losses in magnetic devices
  - Torque reduction in induction motors
  - Excitation of undesirable acoustic modes
  - Electronic equipment problems

- New tighter current specifications
  - 3% or less of fundamental

Figure 45.



HARMONIC CURRENTS CAUSED BY RECTIFICATION
HARMONIC CURRENT AMPLITUDE IN PERCENTAGE OF FUNDAMENTAL
20
15
10
5
RECTIFICATION CURRENTS r = 6
SPECIFICATION CURRENT LIMITS
5
7
11
13
17
19
23
25
29
31
HARMONIC CURRENT NUMBER

Figure 46.

windings on the transformer or by multiple transformers, which produce required phase shifting.[44]

If a transformer is already present, the 31 percent total harmonic distortion (THD) of an r = 6 system can be reduced to the 15 percent THD of an r = 12 system at a reduced kVA rating, with some penalty in size, weight, or cost due to multiple windings. However, in the direct rectification approach, using a transformer for this purpose adds a considerable size, weight, and cost penalty.

MAGNETIZING HARMONICS

Magnetization (transformer) is another source of harmonic currents. The following discussion relies heavily on reference 45 and is supported by references 46 and 47. When an iron core inductance coil magnetic circuit is connected to a sinusoidal single-phase power source, the flux is sinusoidal but the current is not even roughly so. For usual values of flux density in the iron core, the current waveform is peaked. It contains a third-harmonic current component, which may be of the order of 40 percent of the fundamental, and a lesser fifth harmonic, of the order of 10 percent. The magnitude of the harmonic currents is a function of the flux density, the magnetic material, and the air gap. These harmonic currents are necessary to provide a sinusoidal flux in the magnetic circuit and are caused by the nonlinear B-H (flux density versus magnetizing force) curves describing the magnetic properties of iron. Three-phase circuits can be constructed from independent single-phase circuits, such as three separate three-phase transformers or shell-type three-phase transformers (free flux configurations) or from configurations that have common flux paths, such as three-phase core constructions (forced flux configurations). In addition, the coils can be interconnected in delta, wye, or other configurations and, in the case of wye and zig-zag connections, the neutral can be connected or left open. These all affect the amplitude or presence of harmonic currents. Various configurations are discussed in table 3.[48] This table can be used in designing new equipment and in locating areas in which problem equipment may be improved. A similar table could be constructed for motors.

On ships, three-phase loads use ungrounded primaries; as a result, the magnetizing harmonics put on the line contain no third-harmonic components. However, single-phase loads do produce line magnetizing currents with the large-valued third-harmonic component.

ABNORMAL HARMONICS

The assumed conditions in an analysis of rectification (characteristic) harmonics are never exactly fulfilled in practice. Thus, not only are harmonics of characteristic orders slightly changed from their theoretical magnitudes and phases, but also – and this is more important – harmonics of uncharacteristic orders are produced. In usage, a converter is likely to produce harmonics of all orders and some dc component on the rectifier winding of the transformers. These abnormal harmonics arise from imbalances in supply voltages, firing angles, and harmonic voltages in the powerline; they are discussed in more detail in appendix D.

---

[44] Schaefer, J, Rectifier Circuits, Theory and Design, John Wiley and Sons, Inc, 1965

[45] Langlois-Berthelot, R, Transformers and Generators for Power Systems, Their Behavior, Capabilities and Rating, Philosophical Library, NY, 1960

[46] Schaefer, Johannes, Rectifier Circuits: Theory and Design, Wiley, 1965

[47] Grossner, Nathan R, Transformers for Electronic Circuits, McGraw Hill, 1967

[48] NELC Technical Note 2828, Conversion of 400-Hertz Shipboard Electronic Equipment to 60-Hertz Electrical Power Sources, by J Foutz and E Kamm, 7 November 1974

TABLE 3. HARMONIC LINE CURRENTS AS A FUNCTION OF MAGNETIC CIRCUIT AND COIL INTERCONNECTION.

PRIMARY	SECONDARY	LINE CURRENT		FLUX	MISCELLANEOUS
		3rd Harmonic	Waveform		
Δ	Δ Y-N	No	Flattened Sinusoid	Sinusoid	3rd harmonic circulates in delta winding, causing peaked winding current.
Y	Δ	No	Flattened Sinusoid	Sinusoid	
	Y-N	No	Flattened Sinusoid	Nonsinusoid	Highly peaked line-to-neutral secondary voltage waveform which is substantially reduced if forced flux core configuration is used.
Y-N ⏚	Δ	No	Flattened Sinusoid	Sinusoid	3rd harmonic circulates in delta winding, causing peaked winding current.
	Y-N	Yes	Peaked Sinusoid	Sinusoid	3rd harmonic flows in grounded neutral.

1. Free flux configuration unless noted (three independent transformers or shell type 3-phase transformer).
2. The 5th harmonic is always present in the line current and gives a flattened sinusoidal wave shape in the absence of the 3rd harmonic, which peaks the sinusoidal waveform.

HARMONIC SUPPRESSION

The principal methods of diminishing the harmonic output of converters have been

To increase the pulse number.

To install filters.

Newer techniques which show practical promise for the future have been discussed in the literature. These include novel active filters (harmonic injection techniques), multilegged reactors (or transformers), system cancellation techniques, controlled rectification, harmonic frequency transformation, and reduction of abnormal harmonics (see appendix D). However, many of the newer possibilities rely on the use of a transformer.

There seems to be a consensus that if the pulse number is increased from the usual 6, it should not go above 12. Most references state that the reason for this is simply economic. Others, however, make the following more specific claims. The multiplicity and asymmetry of the windings in many 12-pulse and in most above-12-pulse transformers lead to instability, and expensive, low-utility systems are required to restore stable operation. Multiple and asymmetric windings also produce abnormal (or uncharacteristic) harmonics on the ac line.

Depending on the system, the low uncharacteristic orders may have about the same magnitudes as the characteristic harmonics. Magnitudes of uncharacteristic harmonics were found in field tests: 2nd, 5th, 8th, 9th, and 12th harmonics were greater than the 13th for a 12-pulse operation.

Passive filters, even for 400 Hz, are prohibitively bulky and heavy if considerable low-frequency harmonic suppression is required. The problem of impedance mismatching can cause wide discrepancies in filtering parameters. Also, there may be system disadvantages in the use of passive filters, since a shunt-connected filter represents a low-impedance point for ambient harmonics in the power system.

Active filters using solid-state devices can considerably reduce size and weight, though not necessarily cost and complexity. Care must be exercised to avoid positive feedback paths which would cause instability.

The newer techniques have not yet been put into practice, but they do show promise. The harmonic injection technique is appealing: all existing harmonics can be reduced by injecting a third harmonic. Cancellation can also be achieved through the use of properly phased multilegged reactors. Control of the delay and turn-off angles of rectifiers can reduce harmonics sufficiently so that high (0.9) power factors are achieved with many typical loads. Shifting the harmonics to higher frequencies by on-off modulation of conduction during a single half-cycle of rectification may be feasible with today's improved switches and control techniques.

It would appear that the future holds promise for effective harmonic suppression, provided sufficient effort is expended.

PULSE LOADS

The way the electrical power system responds to pulse loads can be another technological problem. Pulse loads are caused by a variety of conditions, including starting of elevators, weighing anchor, and the pulsing of radars and sonars. The electrical generator response to a single step change in load is similar to the familiar response of a well-damped second-order control system. This single response may or may not be a system problem. If the step load is repeated at frequencies related to the characteristic response of the generator, usually between 0.8 and 25 Hz (see fig 47), a modulation of substantial amplitude can occur (80 V peak-to-peak on Type I 440-V ac power). A standard solution to problems of this type has been to specify 400-Hz power and use a motor-generator set as a filter between the ship's 60-Hz system and the pulsing load. The inertia of the MG set is thus utilized to provide the filtering action. MG sets are neither designed nor specified for this filtering application – but they do work. The efficacy of the new solid-state frequency changers as pulse filters has not been shown. In any event, the solution is costly in size, weight, reliability, and dollars, and better solutions are needed.

AD-A043 059 NAVAL OCEAN SYSTEMS CENTER SAN DIEGO CALIF F/G 10/2
REDUCTION OF SHIPBOARD 400-HZ POWER REQUIREMENTS. COST AND TECH--ETC(U)
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UNCLASSIFIED NOSC/TD-107 NL

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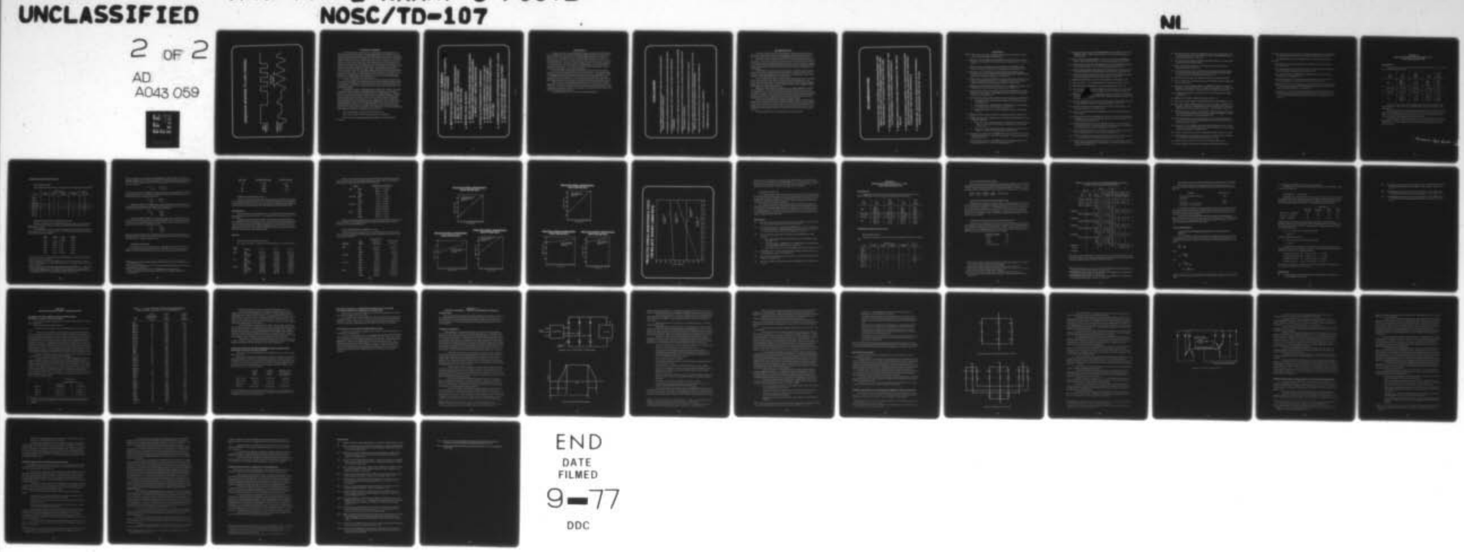

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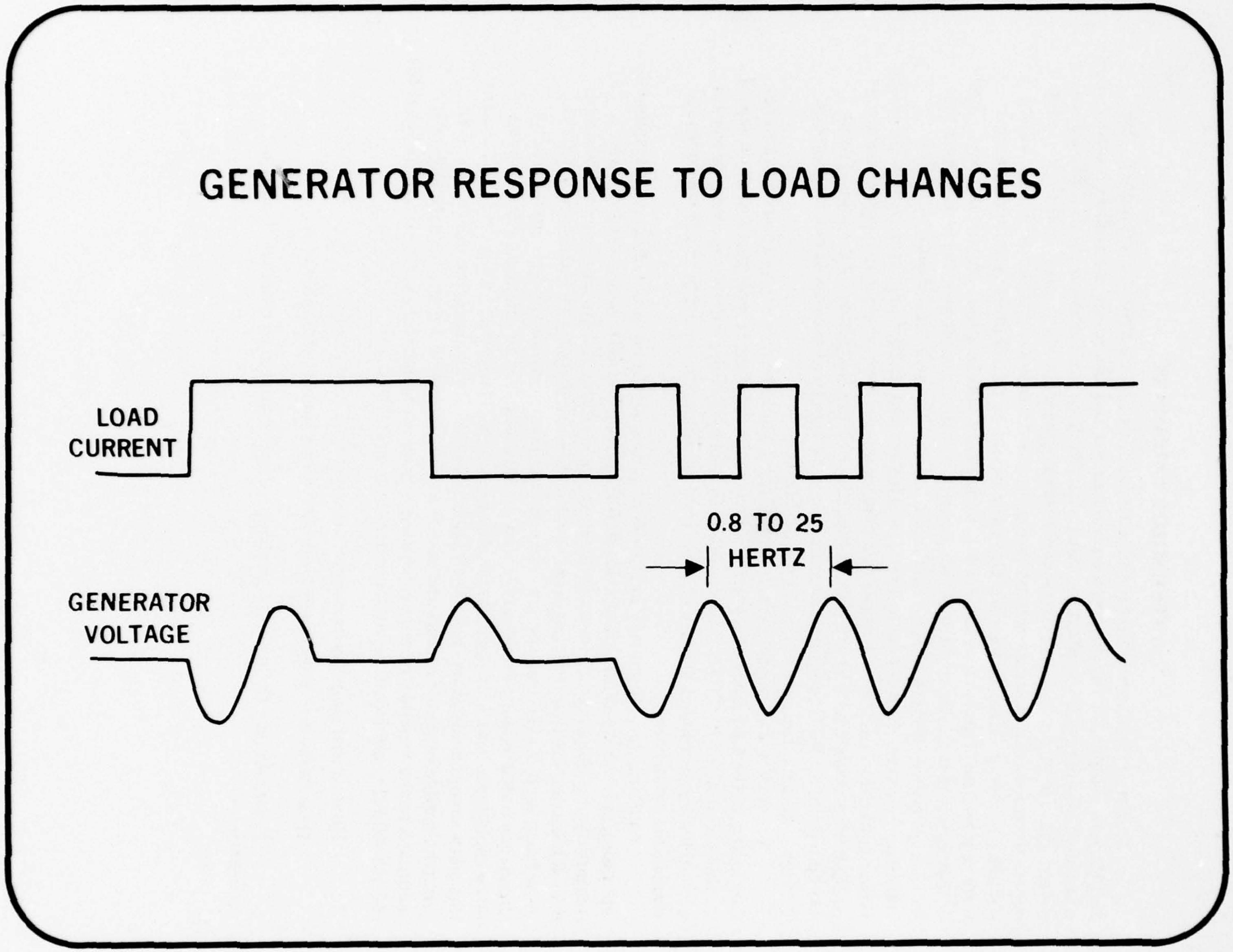
GENERATOR RESPONSE TO LOAD CHANGES
LOAD CURRENT
0.8 TO 25 HERTZ
GENERATOR VOLTAGE

Figure 47.

TECHNOLOGY SUMMARY

This study has shown that the practice of designing electronic equipment to use 400-Hz power input for the purpose of saving weight and size in the electronics is costly when such equipment is specified for ships with 60-Hz prime electrical power. The added weight and size of the frequency changers that must be installed to provide the 400-Hz input negate the minor effect of any weight savings in the electronics. Furthermore, the added complexity creates other problems. The same would be true if 60-Hz equipment power were required on ships such as the PHM-1, which have 400-Hz prime electrical power. Technology exists that allows frequency independent electronic equipment to be designed that will accept either 60-Hz, 400-Hz, or dc input power. The switching regulator power-conversion circuitry in this new technology is lighter and smaller than conventional 400-Hz power-conversion circuitry. It should be kept in mind, however, that to develop electronic equipment and systems that are fully independent of the frequency of the input power would require an R&D program concentrating on a variety of associated electromagnetic devices – motors, fans, blowers, and circuit breakers.

Frequency independent electronic systems would have many potential advantages. For instance, the frequency of a platform power source could be optimized without regard to the electronics. If 400 Hz or some other frequency is more suitable as prime power for certain high-performance ships, a change of power frequency could be made without redesigning the electronics.

As desirable as frequency independent power would be in the long run, the immediate problem is the wastefulness of using 400-Hz power on 60-Hz ships, a system which requires that a frequency changer be installed ahead of the 400-Hz equipment. This problem is less complex than the long-term one and requires little R&D. Switching regulators now being used for the main power conversion in new electronic designs are inherently frequency independent. Fans and blowers are now required to operate on 60-Hz power, even though the associated electronics may require 400-Hz power. Other required electromagnetic components either have both 60-Hz and 400-Hz versions that are form and fit interchangeable (circuit breakers and running time meters) or use an alternate technical approach to the function (servomechanisms). Two problems still exist that require R&D for 60-Hz, 400-Hz, and frequency independent systems. These are

How to best suppress or compensate for harmonic currents.

How to prevent pulse loads from interfering with other equipment.

Figure 48 lists the technological approaches available to eliminate frequency changers.

TECHNOLOGY SUMMARY

TECHNOLOGY/APPROACHES AVAILABLE TO ELIMINATE FREQUENCY CHANGERS

- SWITCHING REGULATORS
  - INHERENTLY FREQUENCY INDEPENDENT
  - SMALLER, LIGHTER, MORE EFFICIENT
  - AVAILABLE AND IN USE
- MOTORS, FANS, BLOWERS
  - SELECT TO OPERATE FROM PRIME POWER SOURCE
  - FREQUENCY-INDEPENDENT DESIGN FEASIBLE
    - MORE COSTLY AND R&D REQUIRED
- OTHER ELECTROMAGNETIC COMPONENTS
  - 60 Hz/400 Hz COMPATIBILITY AVAILABLE
  - ALTERNATE TECHNOLOGY AVAILABLE
  - FREQUENCY-INDEPENDENT DESIGNS FEASIBLE WITH R&D
- HARMONIC CURRENT SUPPRESSION AND PULSE LOADS
  - A PROBLEM FOR 60-Hz AND 400-Hz POWER
  - BETTER SOLUTIONS REQUIRED

Figure 48.

CONCLUSIONS

Frequency changers and a dual distribution system are required on a ship if equipment is installed that uses an input power frequency different from that of the ship's prime electrical source. The major problem is providing 400-Hz requirements on 60-Hz ships. Most ships have 60-Hz prime power but carry much 400-Hz equipment. The practice of providing 60-Hz power on the few high-performance ships with 400-Hz prime power sources is equally troublesome. Frequency changers, required in either case, have high acquisition costs, operating costs, and system penalties. Switching regulator technology is inherently insensitive to the frequency of the input power and is being increasingly used on ships because it has advantages in size, weight, and efficiency.

Properly applied, switching regulator technology reduces the need for frequency changers on ships, with substantial cost savings and system benefits. The required changes can be implemented mostly through education, policy statements, and specification changes; little R&D is directly needed. On the other hand, electronic equipment that is fully independent of powerline frequency is now technologically feasible but would require extensive R&D programs to develop qualified frequency-independent electromechanical parts.

There are two technical problems concerning the power interface that do require R&D efforts to find better solutions than those now available. First, how best to reduce or compensate for harmonic currents in power lines caused by rectification and other electronic equipment nonlinearities. Second, how to suppress or compensate for pulse loads so that they don't degrade the power system.

The key thoughts of these conclusions are tabulated in figure 49.

CONCLUSIONS

- USE OF POWER FREQUENCIES DIFFERENT FROM THE PLATFORM PRIME POWER REQUIRES FREQUENCY CHANGERS
- FREQUENCY CHANGERS HAVE HIGH ACQUISITION, OPERATING AND SYSTEM COSTS
- TECHNOLOGY IS AVAILABLE THAT ELIMINATES THE NEED FOR FREQUENCY CHANGERS
- THE TECHNOLOGY IS BEING USED IN SHIPBOARD ELECTRONICS FOR OTHER REASONS
- PROPER APPLICATION OF THE TECHNOLOGY *WILL REDUCE THE REQUIREMENT* FOR FREQUENCY CHANGERS
- SUBSTANTIAL COST SAVINGS AND SYSTEM IMPROVEMENTS WILL RESULT
- REQUIRED CHANGES CAN BE IMPLEMENTED THROUGH EDUCATION, POLICY STATEMENTS, AND SPECIFICATION CHANGES WITH MINIMUM R&D
- WHETHER IMPLEMENTED OR NOT TWO TECHNICAL PROBLEMS REMAIN
  - REDUCTION OF HARMONIC CURRENTS
  - POWERING PULSE LOADS

Figure 49.

RECOMMENDATIONS

This study concludes that the need for frequency changers can be reduced over a period of years primarily by the processes of education, policy statements, and specification changes. Some technical support to SYSCOMS and contractors will be necessary.

This report is part of the education process necessary to accomplish the change. If the reader is convinced of the validity of the key ideas in this report, he is invited to help in this education process by making the ideas known to others. If the reader is not convinced, he is invited to continue the discussion with the authors or sponsors. Any hidden problems need to be surfaced and resolved to make the process work. Extensive briefings are also recommended.

A NAVMAT policy statement to procure equipment compatible with the platform primary power source would give authority and direction to necessary specification and standards changes and would tighten the control on waivers and deviations. Such a policy statement, in NAVMAT INST format, is recommended.

There is nothing now in the specifications and standards that prevents the designing of electronic equipment that is frequency compatible with the platform prime power source. However, merely a lack of constraint is not sufficient to bring about compatibility. Modification of the specifications, primarily MIL-STD-1399, Sec 103, and MIL-E-16400, is recommended to strengthen them in this area.

While many Navy programs and equipment, such as AEGIS, TRIDENT, AN/UYK-20, and AN/SPG-51, use the switching regulator technology described, they use it with mixed degrees of success. Some acquisition managers and contractors are relatively unfamiliar with the technology. The technical expertise needed by program managers, acquisition managers, and contractors is present in the Navy laboratory structure and in some Navy field activities. It is recommended that this support be made available.

Finally, this study reviewed the technology available to suppress or compensate for harmonic currents and pulse currents in the power distribution system. There are solutions, but this study found none of them fully satisfactory. Various low-level R&D activities are engaged in the search for better solutions, but an expanded effort seems necessary if problems associated with harmonics and pulse currents are to be dealt with in time to support the need.

These recommendations are presented in briefer form in figure 50.

RECOMMENDATIONS

- EDUCATE THE NAVY TECHNICAL AND MANAGEMENT COMMUNITY ON THE COST OF FREQUENCY CHANGERS AND THE OPPORTUNITY TO REDUCE THE NEED FOR THEM
- ESTABLISH A POLICY TO USE POWER AS GENERATED BY THE PLATFORM PRIMARY ELECTRICAL POWER SOURCES
- MODIFY SPECIFICATIONS AND STANDARDS TO IMPLEMENT POLICY
- PROVIDE TECHNICAL SUPPORT TO ACQUISITION MANAGERS AND CONTRACTORS UNFAMILIAR WITH THE REQUIRED TECHNOLOGY AND DESIGN APPROACHES
- EXPAND R&D ACTIVITIES ASSOCIATED WITH HARMONIC CURRENT SUPPRESSION AND PULSE LOADS

Figure 50.

REFERENCES

NOTE: NELC Technical Notes are working documents and do not represent an official policy statement of NOSC (formerly NELC).

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APPENDIX A
PROJECTED MOTOR-GENERATOR MAINTENANCE COSTS FOR FOUR SHIP TYPES

BACKGROUND

Annual maintenance costs for 60-to-400-Hz motor generator (MG) sets were estimated for the following diverse ship types:

Ship types	Old class	Old hull numbers	New class	New hull numbers
DDG	DDG 2	2–14	Same	Same
	DDG 15	15–24	Same	Same
	DDG 31	31–36	Same	Same
DE 1040	DE 1040	1040–1051	FF 1040	Same
DE 1052	DE 1052	1052–1097	FF 1052	Same
DLG	DLG 6	6–15	DDG 37	37–46
	DLG 16	16–24	CG 16	Same
	DLG 26	26–34	CG 26	Same

This report uses pre-July 1975 class designations so they will correspond with the cost data references. The new class names and hull numbers are shown in the above table for reference.

The DE 1040 class was included to provide more representative statistical data. (Since it does not have high-power radars or missiles like the other classes, its inclusion results in a better cross section of ships that use MG sets.) The CV class was excluded because it has only a few ships and low uniformity of armament and radars.

The components of annual maintenance cost – scheduled and corrective maintenance parts and labor, as well as overhaul costs – were totaled for each of the three years, FY 73 through FY 75. The three totals were time plotted, and a least squares line was fitted to each set of points.

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ASSUMPTIONS USED FOR COST STUDY

MG SET POPULATION

The following table lists the MG set population for the four ship types investigated[A1]:

Class	MG sets, qty 30 kW	60 kW	100 kW	200 kW	Ships in class, qty
DDG 2		3	2		13
DDG 15	3	3	2		10
DDG 31		3		2	6
DE 1040	2				10
DE 1052			2		38–46
DLG 6		6		3	10
DLG 16	3	11		3	9
DLG 26	3	5	1	3	9

SCHEDULED (PREVENTIVE) MAINTENANCE (PM)

The labor time required for scheduled maintenance was taken as 32 hours per MG set per year.[A2] Three labor rates were used to test sensitivity of the annual maintenance costs to the labor input.

Low Value (BCM). A tally was made of the maintenance rates listed in the material history reports for the four ship classes for FY 73–75.[A3] The most popular rates and their fractions of occurrence are as follows:

Rate	Weight	Rate	Weight
DS2	0.011	EMFN	0.030
EMCS	0.0083	ICC	0.022
EMC	0.062	IC1	0.096
EM1	0.167	IC2	0.091
EM2	0.271	IC3	0.109
EM3	0.119	ICFN	0.014

[A1] Naval Electronic Systems Command (NAVELEX 5043), EDICT-Electronics Dictionary File, Naval Sea Support Center Pacific, San Diego CA

[A2] Naval Ship Engineering Center letter 6158E/JKM 9610-4 ser 2378 to Naval Sea Systems Command, Subject: 400-Hz Modified Central Power Systems on the DLG 16, 26 and CGN 9 Classes, Life Cycle Cost Study of, 1 July 1975

[A3] Navy Fleet Material Support Office, Maintenance Material Management (3-M) Reports: a. Report MSO 4790-S2704-F-06, Material History Report, 400-Hz Systems, November 1975; b. Tracking Report 2, MSO 47905.3014, FMSO Detection Action Response Technique (DART), 400-Hz MG Sets, August 1975; c. Report MSO 4790.S2711-01, Logistics High Failure Equips, 14 December 1975

The above weights were used with the NAVPERS Billet Cost Model (BCM) to determine an aggregate wage rate; the 1972 data were used for FY 73 and the 1975 data were used for FY 74 and FY 75.[A4] The aggregate annual salaries used for maintenance labor rates in the calculations are as follows:

FY 73:	$15 197.87
74–75:	21 237.11

The work year was taken as 1800 hours, taking into account vacations, holidays, etc.[A5] When an additional factor of 1.3 was added to account for ship support cost[A6] but not tender or shipyard support costs, the hourly rates became

FY 73:	$10.97
74–75:	15.34

Middle Value (SEC). A NAVSEC value of $20 per man-hour was taken for FY 75.[A2] This figure includes ships, tender, and possibly some shipyard support costs. It was deflated 10 percent per year for FY 73 and 74. The hourly rates became

FY 73:	$16.53
74:	18.18
75:	20.00

High Value (NOSC). NOSC Code 744 provided a high value of $28.00 per man-hour for FY 75, which includes ship, tender, and shipyard support costs.* This rate represents the estimated total cost of an E-6 maintenance person. When this rate was deflated 10 percent per year for FY 73 and 74, the hourly rates became

FY 73:	$22.68
74:	25.20
75:	28.00

The major difference between these rates appears to be the amount of overhead allotted to shipboard personnel. However, the three labor rates provide some indication of the sensitivity of the total cost to a change in hourly labor rate.

OVERHAUL COSTS (OH)

Overhaul costs were computed as shown in a NAVSEC letter report.[A4] This report assumed that about 50 percent of the MG sets are overhauled every four years and apportioned 12.5 percent of the overhaul cost each year. The costs computed are given below.

[A4] NAVPERS Report 15163, Navy Military Manpower Billet Cost Data for Life Cycle Planning Purposes, April 1972 and July 1975

[A5] Naval Electronics Laboratory Center TN 1758, Manpower Resource Allocation System, by RA Greenwell and LA Sadler, 3 November 1970

[A6] Presearch Inc, Measure of Benefit Analysis of the SEAMOD Concept (preliminary draft)

*Personal communication from John Townsend, NOSC Code 744, to GL Ruptier, NOSC Code 122, 11 November 1975

Power, kW	Overhaul cost/8 years	Overhaul cost/year
30	$ 7000	$ 875
60	8 000	1000
100	10 000	1250
200	10 000	1250

CORRECTIVE MAINTENANCE (CM)

Corrective maintenance labor and parts data are based on the DART tracking reports for the four ship classes for the years FY 73-75.[A3] The labor and parts costs were totaled for each of the four types of ships for each of the three years. Labor costs were obtained by using the three estimates given above, under Scheduled (Preventive) Maintenance (PM).

METHODOLOGY

The components of annual maintenance cost – scheduled and corrective maintenance parts and labor, as well as overhaul costs – were totaled for each of the three years, FY 73 through FY 75.

A least squares line was fitted to each set of three points, and the forecasted costs were calculated by using the equation of this line. There are a few statistical problems with these estimations, such as a lack of degrees of freedom (due to a lack of data), but the estimates are better than freehand curve fitting or aggregating the data for the three years and assuming an inflation factor. The estimated trend lines are linear; a log-linear estimation was tried, but it produced only slightly different results.

RESULTS

TOTAL ANNUAL MAINTENANCE COSTS

The results of totaling the components of annual maintenance cost are listed below:

Labor rate	Ship type	FY 73	FY 74	FY 75
BCM	DDG	$293 855	$334 605	$307 754
	DE 1040	25 123	28 876	27 073
	DE 1052	142 094	179 380	178 380
	DLG	542 948	639 264	573 387
SEC	DDG	341 721	359 989	343 053
	DE 1040	28 771	30 966	29 944
	DE 1052	161 198	190 331	195 053
	DLG	626 809	686 343	632 639
NOSC	DDG	398 626	424 968	403 653
	DE 1040	33 107	36 317	34 872
	DE 1052	183 910	218 364	223 677
	DLG	726 508	806 858	734 359

Ordinary least squares estimation was used to determine the changing annual maintenance costs over time. The estimated equations are as follows, where t = the number of years since FY 1970 (0 = FY 70, 1 = FY 71, 2 = FY 72, etc):

Model		Estimated cost equation, $k
DDG	BCM	284.27 + 6.9495t
	SEC	345.59 + 0.666t
	NOSC	399.03 + 2.51t
DE 1040	BCM	23.12 + 0.975t
	SEC	27.55 + 0.5865t
	NOSC	31.24 + 0.882t
DE 1052	BCM	94.05 + 18.143t
	SEC	114.48 + 16.927t
	NOSC	129.116 + 19.883t
DLG	BCM	524.32 + 15.219t
	SEC	636.94 + 2.915t
	NOSC	740.21 + 3.926t

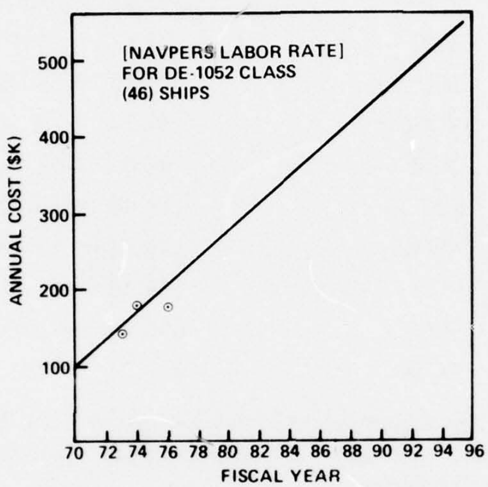
These lines are plotted in figures A1, A2, and A3 for the BCM, NOSC, and SEC labor rates, respectively. These graphs thus show the estimated annual maintenance costs as a function of time for the four ship types.

TOTAL MAINTENANCE COSTS FOR FY 76–90

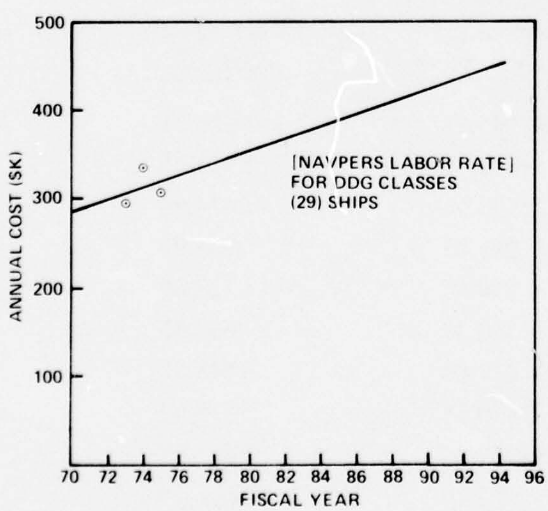
The annual costs were calculated for FY 76–90, discounted by 10 percent per year. The total present (discounted) and undiscounted annual maintenance costs for the 15-year time period are as follows:

Ship type	Labor model	Present (FY 76) discounted costs, $k	Undiscounted costs, $k
DDG	BCM	$3168.45	$ 5619.31
	SEC	3082.42	5313.77
	NOSC	3730.91	6474.90
DE 1040	BCM	298.07	536.96
	SEC	298.37	527.60
	NOSC	359.37	640.53
DE 1052	BCM	2611.83	4948.56
	SEC	2670.18	5018.03
	NOSC	3089.72	5813.93
DLG	BCM	6080.20	10 835.54
	SEC	5847.59	10 122.49
	NOSC	6848.81	11 868.66

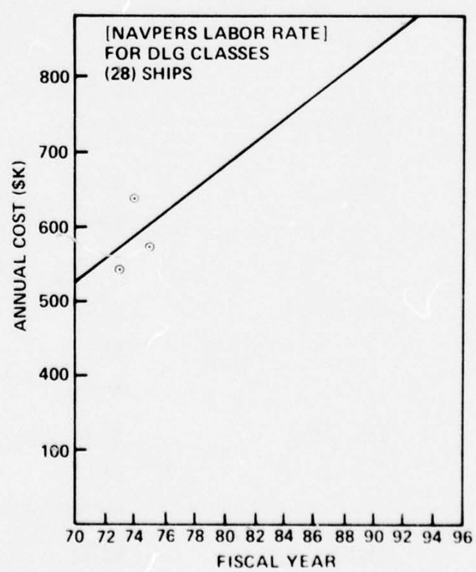
PROJECTED ANNUAL MAINTENANCE COSTS FOR MG SETS



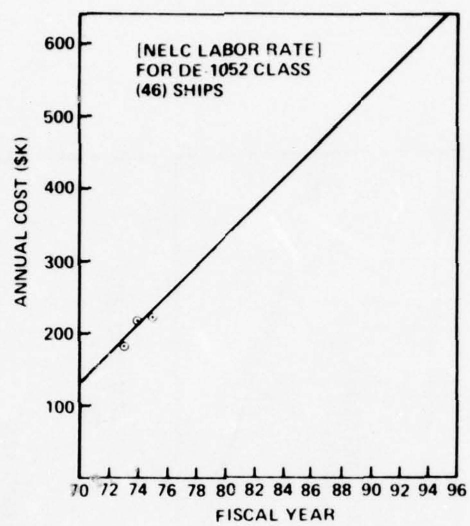
PROJECTED ANNUAL MAINTENANCE COSTS FOR MG SETS



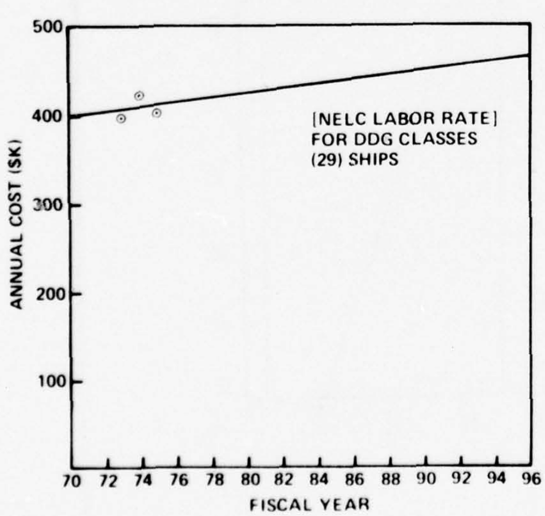
PROJECTED ANNUAL MAINTENANCE COSTS FOR MG SETS



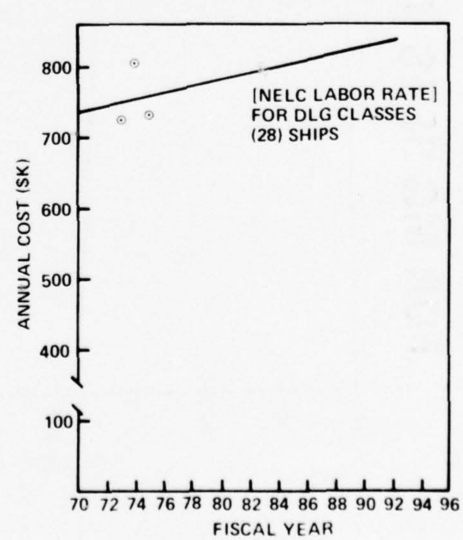
PROJECTED ANNUAL MAINTENANCE COSTS FOR MG SETS



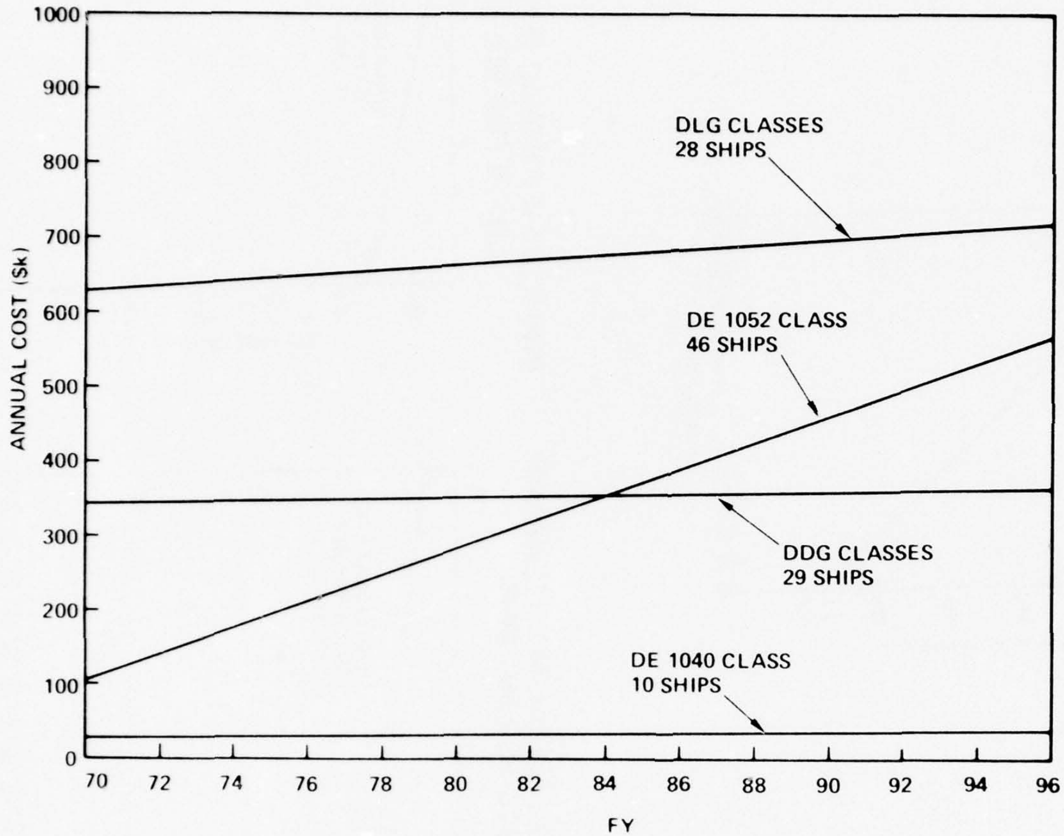
PROJECTED ANNUAL MAINTENANCE COSTS FOR MG SETS



PROJECTED ANNUAL MAINTENANCE COSTS FOR MG SETS



PROJECTED ANNUAL MAINTENANCE COSTS FOR MG SETS [NAVSEC LABOR RATE]



The present (FY 76) discounted costs are the values which should be compared with the present costs of the alternatives to using 400-Hz MG sets in a cost-benefit analysis. Note that the life cycle has been arbitrarily set; the cost figures above are presented only as a coarse indication of the magnitude of the life-cycle maintenance cost of MG sets.

ANALYSIS OF RESULTS

It is evident from these figures that if one type were to be chosen for further analysis, the DLG class type should be the one, because of the high maintenance costs associated with it. Since this class lacks commonality in armament (and hence lacks commonality in heavy 400-Hz power consuming equipment), the cost of modifying each ship type would be different and would have to be analyzed separately.

No conclusion can be drawn from this cost study with regard to which ship type should be modified or whether any at all should be modified. Each type would have different alternatives to using 400-Hz MG sets and each would have to be investigated separately in a cost-benefit analysis. This study did, however, provide estimates of the maintenance cost of 400-Hz MG sets as a function of time, which would be a very important part of any further cost-benefit analysis in this area.

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A3. Navy Fleet Material Support Office, Maintenance Material Management (3M) Reports:

a. Report MSO 4790-S2704-F-06, Material History Report, 400-Hz Systems, November 1975.

b. Tracking Report no 2, MSO 47905.3014, FMSO Detection Action Response Technique (DART), 400-Hz MG Sets, August 1975.

c. Report MSO 4790.S2711-01, Logistics High Failure Equips, 14 December 1975.

A4. NAVPERS Report 15163, Navy Military Manpower Billet Cost Data for Life Cycle Planning Purposes, April 1972 and July 1975.

A5. NELC TN 1758, Manpower Resource Allocation System, by RA Greenwell and LA Sadler, 3 November 1970.

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APPENDIX B
MOTOR-GENERATOR INEFFICIENCY – FUEL COSTS FOR FOUR SHIP TYPES

BACKGROUND

Annual fuel costs of the extra fuel consumed due to the inherent power losses of 60-Hz to 400-Hz MG sets were computed for the following four ship types:

Ship types	Old class	Old hull numbers	New class	New hull numbers
DDG	DDG 2	2–14	Same	Same
	DDG 15	15–24	Same	Same
	DDG 31	31–36	Same	Same
DE 1040	DE 1040	1040–1051	FF 1040	Same
DE 1052	DE 1052	1052–1097	FF 1052	Same
DLG	DLG 6	6–15	DDG 37	37–46
	DLG 16	16–24	CG 16	Same
	DLG 26	26–34	CG 26	Same

ASSUMPTIONS USED FOR COST STUDY

MG SET POPULATION

The MG set populations for the four ship types investigated are listed in the following table.

Class	MG sets, qty				Ships in class, qty
	30 kW	60 kW	100 kW	200 kW	
DDG 2		3	2		13
DDG 15	3	3	2		10
DDG 31		3		2	6
DE 1040	2				10
DE 1052			2		38–46
DLG 6		6		3	10
DLG 16	3	11		3	9
DLG 26	3	5	1	3	9

FUEL COST PER KILOWATT HOUR

The four ship types use steam turbines for the ship service turbine generators (SSTG) that require 0.9 pounds (0.41 kg) of marine diesel fuel (DFM) per kilowatt hour.* The cost of DFM currently averages $26 per barrel.** The density of DFM is 7.10 pounds (3.22 kg) per gallon and there are 42 gallons (0.154 m^3) per barrel.*** Therefore, the cost of DFM is

$$\frac{0.9\ \text{lb}}{\text{kW}\cdot\text{h}} \times \frac{1\ \text{gal}}{7.10\ \text{lb}} \times \frac{1\ \text{barrel}}{42\ \text{gal}} \times \frac{\$26}{1\ \text{barrel}} = \$0.0785/\text{kW}\cdot\text{h}$$

EFFICIENCY OF MG SETS FOR FOUR SHIP TYPES

Efficiency data for the different types of MG sets on the ships studied were obtained from the NAVSEC Project Engineer for 400-Hz motor-generators. Data were obtained for 1/2, 3/4 and full-load conditions.**** The half-load efficiency data were used for all calculations, although the actual loads for the ship modes of operation used in the calculations varied from 0.5 to less than 0.2. Since the efficiency decreases with decreasing load, the dissipative fuel cost estimates are low. The efficiency at half-load varied from 61 to 85 percent, as shown in table B1.

CONNECTOR LOADS AND LOAD FACTORS FOR MG SETS

Load factors when multiplied by the connector load (rated kW input) for each shipboard equipment or group of equipments will give the demand load of the equipment(s) for each condition of operation (such as shore, anchor, cruising, or battle). Reference B1 discusses the selection of operating load factors for surface ships. Typical load factors (LF) for 400 MG sets on aircraft carriers and destroyers are as follows:

Operating Condition	LF
anchor	0.2
shore	0.2
cruising	0.5
functional (battle)	0.7

*Telecon between J Brady, NAVSEC 6156D, and E Kamm, NOSC 7434, 11 March 1976, referencing data obtained from D Libby, NAVSEC 6144B, by Mr Brady

**Telecon between E Kamm, NOSC 7434, and M Spivack, NSEC 6156D, 16 March 1977

***Telecon between J Brady, NAVSEC 6156D, and E Kamm, NOSC 7434, 11 March 1976, referencing data obtained from E Davis, NAVSEC 6101F, by Mr Brady

****Telecon between A Nickley, NAVSEC 6158C, and E Kamm, NOSC 7434, 12 March 1976

[B1] Naval Ship Engineering Center Design Data Sheet DDS 9610-2, Design Details of Generating Plants, 1 May 1970

TABLE B1. EXTRA CONNECTED POWER REQUIREMENTS DUE TO MG INEFFICIENCIES FOR FOUR SHIP TYPES.

	Ship class: Old name	Ship class: New name	MG sets: kW rating	MG sets: Qty	MG sets: Efficiency, %	MG sets: kW conn (Po)	Extra kW required per ship (Pe)	Qty of ships	Total extra kW required	Total qty of MG sets
	DE 1040	FF 1040	30	2	64	15	8.4*	10	84	20
	DE 1052	FF 1052	100	2	72	107	41.5	46	1909	92
	DDG 2-24	DDG 2-24	100	2	74	43	15.1			
			60	3	73	80	29.6			
			30	3	61	37	23.7			
SUBTOTAL				5			68.4	23	1573	184
	DDG 31-36	DDG 31-36	200	2	65	170	91.6			
			60	3	73	80	29.6			
SUBTOTAL				5			121.2	6	727	30
	DLG 6-15	DDG 37-46	200	3	65	276	148.6			
			60	6	68	272	128.0			
SUBTOTAL				9			276.6	10	2766	90
	DLG 16-24	CG 16-24	200	3	85	276	48.7			
			60	11	68	459	216.0			
			30	3	70	46	19.7			
SUBTOTAL				17			284.4	9	2560	153
	DLG 26-34	CG 26-34	200	3	85	276	48.7			
			60	5	68	200	94.1			
			100	1	72	60	23.3			
			30	3	70	46	19.7			
SUBTOTAL				12			185.8	9	1672	108
TOTAL									11 291	677

*Estimated

Data for the connected loads (kW conn) and load factors were obtained from references B2, B3, and B4. Reference B2 contains six enclosures consisting of power analyses and 400-Hz single-line diagrams for DE 1052, DDG 2 and DLG 16 classes.

[B2]Naval Ship Engineering Center Transmittal Letter SEC 6156D/JAB 9600 ser 3865 to Naval Electronics Laboratory Center, Subject: Power Analysis, 26 December 1974

[B3]NAVSHIPS Drawing 81994/302/4350329 by NAVSEC ltr 6155C; EMO 9620 ser 539; 400-Hz Power System Single Line Diagram DDG 31, 15 February 1973

[B4]NAVSHIPS Drawing 81994/302/4350134 by NAVSEC ltr 6155C; EMO 9620 ser 619, 400-Hz Power System Single-Line Diagram DLG 6 thru DLG 15, 2 March 1973

HOURS PER YEAR FOR VARIOUS OPERATING CONDITIONS OF THE SHIPS

Data for typical annual hours of operation for different ship conditions were obtained from NAVSEC 6144B, the Surface Ships Section of the Propulsion Systems Analysis Branch.*

Condition	Hours per year
Cold iron (powered by other than own power)	1760
At anchor	3500
Underway (cruise: 90 to 99 percent; battle: 1 to 10 percent)	3500

For purposes of this study, it was assumed that the ships operate for 3500 hours per year at the cruise mode and zero hours at battle mode. It was also assumed that fuel cost per kilowatt hour when the ship is powered by external power is the same as fuel cost per kilowatt hour when the ship is underway.

To account for daily and seasonal variations in the usage of shipboard power, a figure of only 80 percent of the above hours was used in the calculations. A NAVSEC study found 80 percent to be the average annual electrical load usage for the cruise mode.† The same percentage was assumed for the other modes.

CALCULATED RESULTS

EXTRA CONNECTED POWER REQUIRED DUE TO INEFFICIENCY OF MG SETS

If P_1 is the MG set connected power requirement from ships service power, P_0 is the connected load to the MG set, and η is the efficiency of the MG set (percentage), then the extra quantity of power, P_e, required to be connected to the ship's 60-Hz power is $P_1 - P_0$, where

$$\frac{P_0}{P_1} = \frac{\eta}{100}.$$

Thus,

$$P_1 = \frac{100 P_0}{\eta}$$

and

$$P_e = \frac{100\, P_0}{\eta} - P_0$$

$$= P_0 \left(\frac{100 - \eta}{\eta}\right) .$$

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*Telecons between D Libby, NAVSEC 6144B, and E Kamm, NOSC 7434, 26 March 1976 and 9 April 1976
†Ibid.

If, for example, P_0 = 200 kW and η = 75%, then P_e = 66.7 kW.

Table B1 lists the extra connected power requirement due to the inefficiency of MG sets for the four ship types.

INEFFICIENCY – FUEL COSTS

Calculations were performed to determine the annual fuel costs – first, for each kW of connected loads to ship's 60-Hz power (prior to frequency conversion). From data under the headings, "Connector Loads and Load Factors for MG sets" and "Hours Per Year for Various Operating Conditions of the Ships," the following load factors were used:

	Load factors			
	DE 1052	DE 1040	DDG	DLG
Cruise mode – 3500 hours	0.4	0.4	0.5	0.5
Cold iron – 1760 hours	0.2	0.2	0.2	0.2
Anchor – 3500 hours	0.2	0.2	0.2	0.2

Using an 80 percent average annual power usage factor with the cost of DFM fuel at \$0.0785 per kilowatt hour (see para titled "Fuel Cost Per Kilowatt Hour") and designating A as the annual fuel cost for each kW of connected load to 60-Hz power, then, for the DE 1052 and DE 1040 classes,

$$A = (0.4 \times 3500 + 0.2 \times 5260) \times 0.8 \times \$0.0785$$
$$= \$154.02$$

And for the DDG and DLG Classes,

$$A = (0.5 \times 3500 + 0.2 \times 5260) \times 0.8 \times \$0.0785$$
$$= \$176.02.$$

To calculate the total annual fuel costs, let B = annual fuel costs due to the inefficiency of the MG sets for each ship type. Then the total extra kW required (from table B1) multiplied by A results in the following breakdown:

For DE 1052 (42 ships): B = \$154.02 × 1909 = \$ 294 046

For DE 1040 (10 ships): B = \$154.02 × 84 = \$ 12 938

For DDGs (29 ships): B = \$176.02 × 2300 = \$ 404 841

For DLGs (28 ships): B = \$176.02 × 6998 = \$1 231 771

Thus for the four ship types, consisting of 113 ships, the annual fuel costs attributable to the inefficiency of the MG Sets are \$1 943 596.

REFERENCES

B1. Naval Ship Engineering Center Design Data Sheet DDS 9610-2, Design Details of Generating Plants, 1 May 1970.

B2. Naval Ship Engineering Center Transmittal Letter SEC 6156D/JAB 9600 ser 3865 to Naval Electronics Laboratory Center, Subject: Power Analysis, 26 December 1974.

B3. NAVSHIPS Drawing 81994/302/4350329 by NAVSEC ltr 6155C; EMO 9620 ser 539; 400-Hz Power System Single Line Diagram DDG 31, 15 February 1973.

B4. NAVSHIPS Drawing 81994/302/4350134 by NAVSEC ltr 6155C; EMO 9620 ser 619, 400-Hz Power System Single Line Diagram DLG 6 thru DLG 15, 2 March 1973.

APPENDIX C
400-Hz CENTRALIZED SYSTEMS – STUDIES AND TESTS

FEASIBILITY OF 400-Hz MODIFIED CENTRAL POWER SYSTEM ON THE DLG 16, DLG 26, AND CG 9 CLASSES

(This study is reported in NAVSEC letter 6155C/RGT 9610-4, serial 997, to NAVSEA, 23 April 1975.)

This study was tasked with three objectives:

1. Determine relative reliability of the various 400-Hz power systems on surface ships.

Calculations were performed to measure the relative material condition index, which is a common statistic used to measure the operational readiness of a particular piece of equipment based on the number of casualties suffered, the severity of each casualty, and the average downtime following each casualty. Table C1 lists the annual casualty rate per motor-generator for each class and the material condition index normalized by the MG population of each class. The lower the normalized material condition index, the greater the operational readiness of the 400-Hz motor-generators on that ship class for the 2-year period of record. For the 43 ship classes analyzed, the sample average normalized material condition index was 2.81. It was pointed out that this index is not a true measure of operational readiness; all 400-Hz systems are designed with redundant motor-generators so that even ships with very high material condition indexes support complete combat operations.

2. Design two hypothetical more centralized 400-Hz systems for the DLG 16, DLG 26, and CG 9 classes. Evaluate the benefits thereby obtained.

One proposed system envisioned the use of 150-kW Teledyne-Inet solid-state frequency changers as ship service power only and assumed that all 400-Hz loads are compatible. A second proposed system was more realistic but still hypothetical. It presumed satisfactory operation of ship service loads, the Naval Tactical Data System, search radars, and the interior communication system – all powered, from a central bus, by the solid-state changers. (The validity of this presumption is still to be determined.) This more realistic system, therefore, assumed fewer dedicated MG sets but still proposed dedicated MG sets for the Terrier and/or Talos fire control systems. The only benefit considered by this study was the weight savings benefit listed below (difference in weight between the MGs removed and the solid-state changers added):

Ship class	Weight savings (pounds (Mg) per ship)	
	*Complete centralization	Partial centralization
DLG 16	43 500 (19.7)	24 000 (10.9)
DLG 26	47 400 (21.5)	40 400 (18.3)
CGN 9	53 600 (24.3)	41 300 (18.7)

*Complete centralization weight savings are not realistic at this time but were presented to illustrate the weight penalty that existing 400-Hz systems suffer because user loads are not all designed to be compatible.

TABLE C1. CASUALTY RATE OF 400-HZ MOTOR GENERATORS ON SURFACE SHIPS, 1 JANUARY 1973 TO 31 DECEMBER 1974.

Ship class	Total motor-generators (MG population) per class	Casualty rate per year per MG	Material condition index normalized
AOE 1	6	0.333	15.92
MSO 422	28	0.339	13.20
DD 710	88	0.301	8.28
DDG 31	20	0.300	7.13
LCC 19	8	0.312	6.89
MSO 508	4	0.250	6.19
DD 945	10	0.400	5.89
CVA 41	13	0.154	5.03
DE 1037	4	0.250	4.72
DE 1033	8	0.062	3.94
AR 28	1	0.500	3.90
DE 1078	42	0.214	3.54
DD 931	16	0.125	3.40
AFS 1	14	0.107	3.27
DLG 6	101	0.089	3.14
AOR 1	12	0.292	2.82
DDG 2	183	0.139	2.77
CVA 59	19	0.105	2.56
DE 1052	56	0.178	2.50
DDG 35	10	0.250	2.34
DE 1040	22	0.159	2.22
CVA 63	52	0.096	2.15
AE 26	24	0.021	1.65
DER 329	2	0.250	1.60
MSC 200	7	0.143	1.47
AGDE 1	2	0.250	1.40
DLG 26	110	0.073	1.38
DLG 16	155	0.052	1.15
AO 51	6	0.083	1.12
DD 825	4	0.125	1.12
CG 10	57	0.114	0.94
LPH 2	36	0.111	0.92
DE 1021	12	0.042	0.82
LPD 4	60	0.075	0.68
DLGN 25	12	0.042	0.67
DEG 1	30	0.100	0.57
CVS 1	21	0.048	0.34
CLG 4	14	0.036	0.24
PG 84	17	0.088	0.24
CGN 9	22	0.023	0.20
LSD 36	10	0.050	0.20
LST 1179	40	0.012	0.05
LKA 113	15	0.033	0.03

3. Make recommendations on the future design of 400-Hz power systems.

The weight savings attributable to a modified central 400-Hz power system is significant if it can be achieved during new construction or overhaul. Weight savings on existing ships impact the ship's moment. MG sets on steam propulsion ships such as the DLG 16, DLG 26, and CGN 9 classes are traditionally located very low in the hull. Thus the weight savings would appear at or below the center of gravity. The stability effect would range from a neutral moment impact (on the DLG 26 class) to an increase in required ballast to offset the weight decrease (on the CGN 9).

Since radar guidance systems (such as the Terrier system) require more MG sets than any other user load, the conversion of guidance radar systems to 60-Hz input would do more for the centralization of the 400-Hz system than any other single effort. NAVSEC recommends that projects such as the Line Independent Power Supply (LIPS), designed by Raytheon for the AN/SPG-41 TARTAR radar system, be vigorously pursued. It demonstrates that sufficient technology exists to permit 60-Hz excitation of large radar loads along with realization of space and weight savings in both the radar and power systems.

The benefits of converting an existing 400-Hz system are much less than the cost of such a conversion. Therefore, NAVSEC did not recommend the installation of a 400-Hz modified central power system on the DLG 16, DLG 26, or CGN 9 classes.

LIFE CYCLE COST STUDY OF 400-Hz MODIFIED CENTRAL POWER SYSTEM ON THE DLG 16, DLG 26, AND CGN 9 CLASSES

(This study is reported in NAVSEC letter 6158E/JKM 9610-4, serial 2378, to NAVSEA, 1 July 1975.)

This study was requested to complement the information contained in the feasibility study discussed above. The life-cycle costs considered are those costs which would be incurred from FY 76 until the end of ships' lives for the proposed systems. One-time (initial) and yearly costs were used to calculate life-cycle cost (LCC) of 60- and 400-Hz power conversion systems for three configurations on DLG 16, DLG 26, and CGN 9 classes. Total life-cycle costs of the systems are as follows:

	Existing systems (MGs)	Centralized systems (SSFCs)	Modified systems (combination of MGs and SSFCs)
DLG 16 class	$4 887 148	$13 203 918	$9 428 949
DLG 26 class	5 100 238	11 252 385	8 496 819
CGN 9 class	657 681	2 173 641	1 651 223
TOTAL	$10 645 067	$26 629 944	$19 576 991

The above table indicates, both by classes and in total, that LCC of the centralized systems is approximately three times higher, and that of the modified systems approximately two times higher, than LCC of the existing systems.

USS TRUXTUN (DLGN 35): COMPATIBILITY CHECKS AND EVALUATION OF 60/400-Hz SOLID-STATE FREQUENCY CHANGERS (SSFC)

(These tests are reported in NAVSEC letter 6732:JK:lml 9620/DLGN 35 FT-4619, serial 205, to NAVSEC 6155C, 9 Oct 1974.)

Prior to shipboard testing, preliminary land based evaluation tests were made of two Teledyne-Inet SSFCs. In these tests, the SSFCs powered a dummy load and an SPS-48A in parallel with a Univac 1230 computer. The SSFCs showed some problems but gave better performance than MGs. Shipboard testing of the SSFCs was therefore recommended.

USS TRUXTUN (CGN 35) 400-Hz SYSTEM INTERFACE TEST

(These tests are reported in NAVSEC letter 6732:JK:gl 9320, FT-4300, serial 42, to NAVSEC 6155, 23 March 1976.)

The two units evaluated in the previous paragraph were installed aboard USS TRUXTUN, and interface compatibility tests were conducted in June 1975. These tests revealed that some grouping of loads is possible with SSFCs. (The SPS-48A is compatible with other 400-Hz loads.) However, the AN/SPG-55B radar still requires dedicated power. Thus SSFCs appear to require fewer dedicated MG sets. There are, however, still considerable problems with SSFC hardware maintainability and reliability. Furthermore, these were short term tests; the final phase of testing (endurance) will take the form of continued operation of the SSFCs aboard USS TRUXTUN under all conditions, stressing battle conditions.

APPENDIX D
POWERLINE HARMONICS – POTENTIAL SUPPRESSION TECHNIQUES

INTRODUCTION

Several new harmonic suppression techniques proposed in the literature are reviewed here. Depending on the system, uncharacteristic harmonics may arise on the powerline. Therefore, papers which are reviewed discuss the origin and suppression techniques for these abnormal harmonics. A paper describing a method of reducing three-phase filter losses is also summarized.

ABNORMAL HARMONICS

Voltage imbalance in a three-phase powerline creates some 5th and 7th harmonic currents even with 12-pulse operation; and unequal firing angles (α) of controlled rectifiers (fig D1 and D2) generate even harmonics, triplen harmonics (multiples of the third), and a dc component in the powerline. Controlled rectification with a conventional control system, when combined with a high ac system impedance, can result in harmonic instability due to magnification of abnormal harmonics by the converter. Harmonic voltages in the powerline (either balanced or unbalanced) change and unbalance the angles of overlap during commutation, and these angular differences in turn cause abnormal currents to flow in the powerline. Five references speaking to these abnormal harmonics are discussed below. The fourth paper describes a control system that reduces abnormal harmonics without the use of filters.

1. Kimbark[D1] states that several high-voltage dc terminals experienced improper operation and even instability from large-amplitude low-order uncharacteristic harmonics. The instability results from harmonic oscillation that can occur if the loop gain of the system is high enough. Field tests were made with the filters disconnected for 6- and 12-pulse operation. The results showed that 2nd, 5th, 8th, 9th, and 12th harmonics had amplitudes greater than the 13th for the 12-pulse operation. The 6-pulse operation had lower-amplitude abnormal harmonics than the 12-pulse operation.

2. An IEEE paper[D2] provides an analysis of unusual harmonics appearing on the waveform as a result of operation of high-voltage dc converters. These harmonics are called unusual (or abnormal) because they are not expected from the existing theory relating to balanced operation. The paper analyzes uncharacteristic harmonics from two sources: firing angle and supply voltage imbalance. They are considered both individually and in conjunction, when the two effects become interdependent.

The individual variables in this problem progressively increase in number as degrees of imbalance are introduced. Each rectifier firing, for example, can be individually specified; the permutations for relative imbalance are large for 6-pulse operation and even larger for 12-pulse operation. Therefore, the technique adopted was to select representative cases indicative of the wide range of harmonic behavior.

A computer program is described which enables harmonics, both characteristic and uncharacteristic, to be predetermined for any specified conditions of imbalance for 6- and 12-pulse operation. With unbalanced voltages in 12-pulse operation, the complementary harmonics (5th, 7th, etc) have neither magnitude nor phase relations that match. Hence these harmonics are injected into the ac system. For both 6- and 12-pulse operation the effect of ac imbalance is to introduce third and other triplen harmonics. For unequal firing angles

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[D1] Kimbark, EW, Direct Current Transmission, volume 1, p 318-322, Wiley Interscience, 1971

[D2] Reeve, J and Krishnayya, PCS, Unusual Current Harmonics Arising from High Voltage DC Transmission, IEEE Transactions on Power Apparatus and Systems, v PAS-87, no 3, p 883-893, March 1968

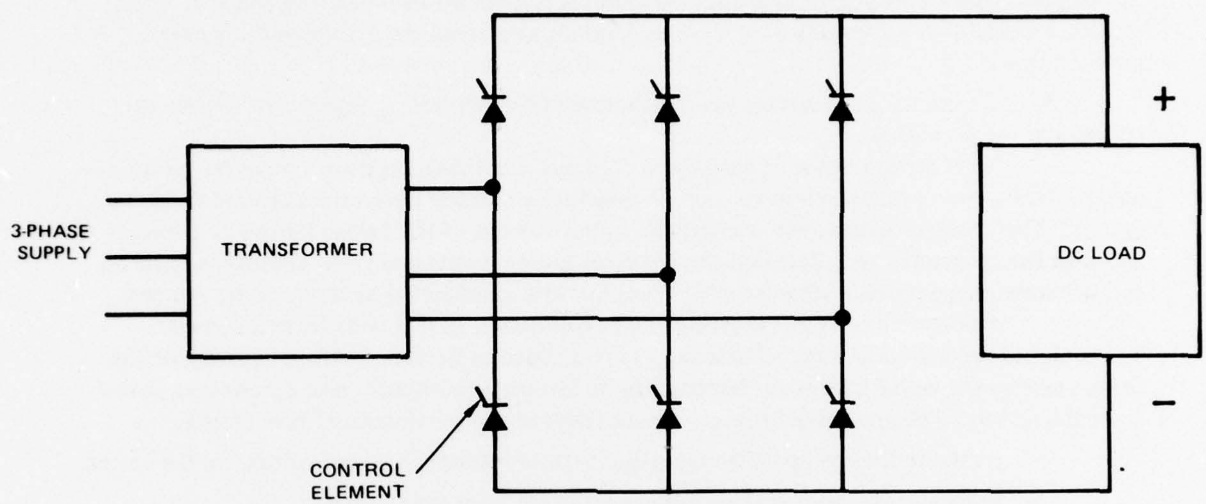

Figure D1. Ac to dc rectifier (full-wave three-phase bridge).

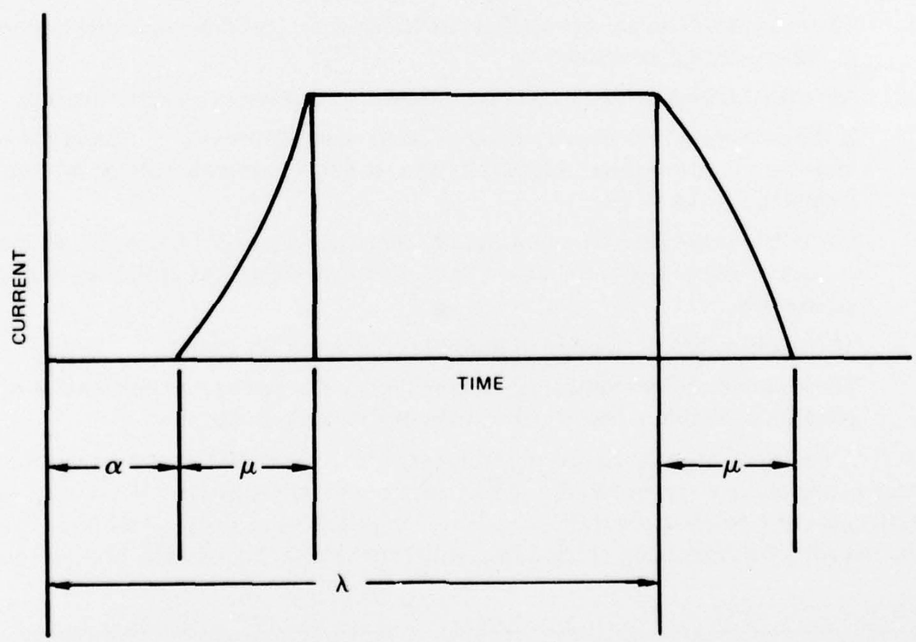

Figure D2. Controlled rectification waveshape.

(with or without voltage imbalance), even harmonics are generated with a dc component in addition to the triplen harmonics. The dc problem could drive the transformer into saturation.

The authors conclude that one of the uncertainties is the level of harmonics that can be permitted to propagate into an ac system. It is difficult to predict localized resonant effects, especially in a complex ac system undergoing continual short-term and long-term modifications.

3. Reference D3 analyzes yet another source of abnormal harmonics – harmonic voltages in the powerline.

With certain types of automatic controls, the firing angles of converter rectifiers may sustain some errors which in turn could generate abnormal harmonic currents in the ac system. The analysis herein assumes that the direct current of the bridge has no ac component and that the controlled rectifiers (valves) are ideal short circuits and open circuits in their on and off states respectively. However, the commutating reactance is assumed to be nonzero.

The source of errors in firing angles considered here results from assumed harmonics in the ac bus voltage. These errors are defined as deviations from equality of the firing angles. The deviations occur because the firing-angles computer also receives its power from the ac bus. The analysis of this ac voltage feedback loop consists of three tasks.

Evaluate the firing-angle errors due to an assumed harmonic voltage on the ac line.

Evaluate the abnormal harmonics resulting from these errors.

Calculate the system impedance to determine whether the possibility of sustaining this harmonic exists. This system impedance is the product of the transfer function which couples the ac system bus with the control system ac bus and the impedance of the main ac system.

The conclusions reached are as follows:

The individual controlled rectifier converters may generate abnormal harmonics in the connected ac system.

Abnormal harmonic generation is more likely at heavier converter loading.

If the ac system impedance assumes a large value (approaching infinity) at some frequency, the converter may excite and sustain a harmonic voltage of that frequency at the ac bus.

Since the control bus coupling circuit affects the abnormal harmonic generation, it can be used as a tool to correct undesirable conditions of abnormal harmonic generation.

This analysis can be applied to multiple converters per terminal.

These abnormal harmonics will be small (only due to random errors) if it is possible to abandon individual control of the firing angles.

4. A new type of pulse timing control system is described[D4] that removes the direct dependence of the control system on the ac line voltage and its distortion. It makes possible the operation of converters on relatively weak (high-impedance) ac systems, without harmonic instability and with low generation of harmonics other than those theoretically present (normal).

[D3] Phadke, AG and Harlow, JH, Generation of Abnormal Harmonics in High Voltage AC-DC Power Systems, IEEE Transactions on Power Apparatus and Systems, v PAS-87, no 2, March 1968

[D4] Ainsworth, JD, The Phase-Locked Oscillator – A New Control System for Controlled Static Converters, IEEE Transactions on Power Apparatus and Systems, v PAS-87, no 3, p 859-865, March 1968

With conventional control systems and with an ac system of sufficiently high impedance at abnormal harmonics, there is a possibility of harmonic instability due to magnification of abnormal ac line voltage harmonics by the converter (discussed under item 3).

Small filters rated at a few watts are normally connected between the main voltage transformer and the control system to attenuate these harmonics.

The phase-locked oscillator control system described here has progressive advantages over conventional control systems as the ac system becomes weaker, giving better performance by reduction of abnormal harmonics without the use of abnormal harmonic filters.

In the appendix to the referenced paper, the author discusses other effects such as the following:

An ac harmonic filter will usually be designed to have resonances at characteristic harmonics of orders of 5, 7, 11, 13, etc. However, the parallel combination of ac filter and ac system will have many intermediate antiresonances or "natural frequencies." These natural frequencies are excited (ie, ringing is caused) by any ac system disturbance or by any current transient from the converter, and they may take many cycles to die away. The dominant ringing frequency is usually just below 5th harmonic, if the lowest tuned filter arm is for 5th harmonic. Ringing can cause commutation failure. Conventional controls can magnify the ringing caused by line transients, whereas the phase-locked system remains passive. For this reason, from the point of view of commutation failure, conventional control systems are very much worse when the ac system is weak (short-circuit ratio of 4 or less).

5. A general programming approach is presented[D5] to compute the harmonics resulting from any combination of supply-voltage harmonics, fundamental voltage imbalance, and firing angle perturbation, for both 6- and 12-pulse operation. The results obtained were for open loop computation wherein it is assumed that the harmonic voltage content of the supply waveform can be specified and that the resultant line current harmonics can then be computed. The authors state that the computational techniques could easily be adapted to closed loop analysis but would require excessive computation time. Closed loop analysis would require iteratively modifying the harmonic voltage levels by the interaction of generated current harmonics with the ac system impedance.

Even with the open loop analysis there were too many variables to present generalized graphs of harmonics. As a compromise, harmonics computed for arbitrarily selected combinations of variables are presented. Graphs are presented which show the computed harmonic currents obtained with 3rd, 2nd and 8th harmonic voltage levels (in powerline) and which include the effect of a perturbation of firing angle (α) of 0.5 percent.

The paper concludes that practicable levels of voltage harmonic distortion do not lead to large abnormal harmonic currents. However, it suggests that in certain circumstances they may be significant. Some of its conclusions follow:

Even-order unbalanced harmonics, in the supply voltage, result in the generation of current harmonics of every order.

Odd unbalanced harmonics produce a spectrum of all odd current harmonics.

Balanced, even harmonic voltages result in a complete current harmonic spectrum, excluding triplen harmonics.

Balanced odd harmonics result in all odd current harmonics, excluding triplen harmonics.

[D5] Reeve, J, Baron, JA, and Krishnayya, PCS, A General Approach to Harmonic Current Generation by HVDC Converters, IEEE Transactions on Power Apparatus and Systems, v PAS-88, no 7, July 1969

In all cases, a complete harmonic spectrum of currents results from the introduction of an α perturbation (see fig D2).

For balanced voltage harmonics, both considered modes of control* behave identically. With unbalanced voltage harmonics, the equal-pulse-spacing type appears to give lesser magnitudes of abnormal harmonics without altering their order.

Of the abnormal current harmonics resulting from a certain voltage harmonic, the frequency of the largest is not necessarily that of the voltage harmonic.

Voltage harmonics arising because of balanced triplen-frequency ac system resonance will not be reinforced by current generation at the same frequency, excluding the effects of firing angle errors.

Even-harmonic resonance, particularly at a frequency below the effective range of low-pass filtering, could be a more serious problem, especially if further aggravated by control errors.

Note: The discussion following the presentation of this last paper was critical of the open loop analysis and indicated that without the feedback loop it is not possible to assess whether or not ac system voltage harmonics will be further exaggerated by the converter operation.

REDUCING FILTER LOSSES

A simple and effective idea for reducing ac filter losses in three-phase systems is described in reference D6.

Conventional series resonant filters, as shown in figure D3, are commonly connected to the ac terminals of a converter to supply a shunt path for harmonic currents. Filters tuned to the kth, lth and mth harmonics might in practice correspond to the 5th, 7th and 11th harmonics. When automatic tuning is not employed, the Q of each filter branch must be low enough to maintain moderate detuning. Accordingly, significant power loss is incurred in the resistors included in each filter branch (supplementing the resistance of the inductors).

Figure D4 shows a three-phase interconnected filter using three resistors instead of the conventional nine. The author claims fundamental power losses are thereby significantly reduced, while the harmonic performance is essentially unchanged.

The harmonic analysis presented is not rigorous but has been supported by experiment and computer analysis. A computer program is available to aid in optimization of the filter design for a specific application.

This idea, however, may have only limited application for the Navy, since it appears to require a neutral bus, which is usually not available on Navy ships.

HARMONIC REDUCTION IN CONVERTERS BY HARMONIC CURRENT INJECTION

Several papers have been written describing novel active filter methods of reducing line current harmonics, in which the shape of the current waveform is modified by injection of harmonic currents into the converter. Three such papers are reviewed here.

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*Equal pulse spacing (as contrasted with equal delay angles) is the type of control incorporating the phase-locked oscillator principle discussed in item 4.

[D6]Gilsig, R, An Interconnected AC Filter for HVDC Converters, IEEE Transactions on Power Apparatus and Systems, v PAS-89, no 3, p 463-469, March 1970

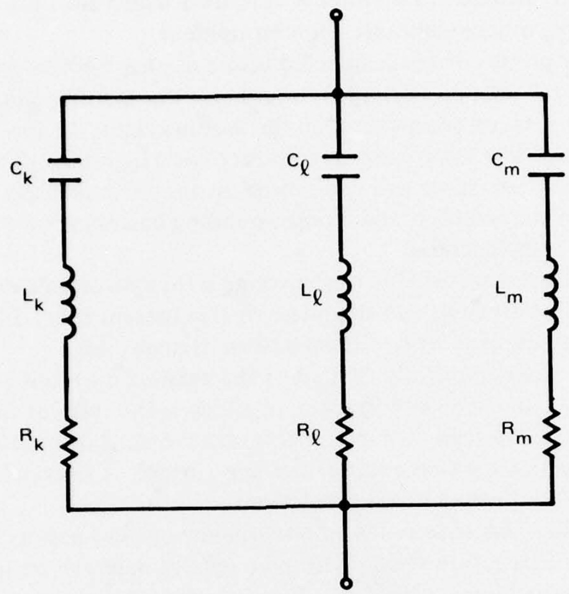

Figure D3. Conventional single-phase series-resonant filter bank.

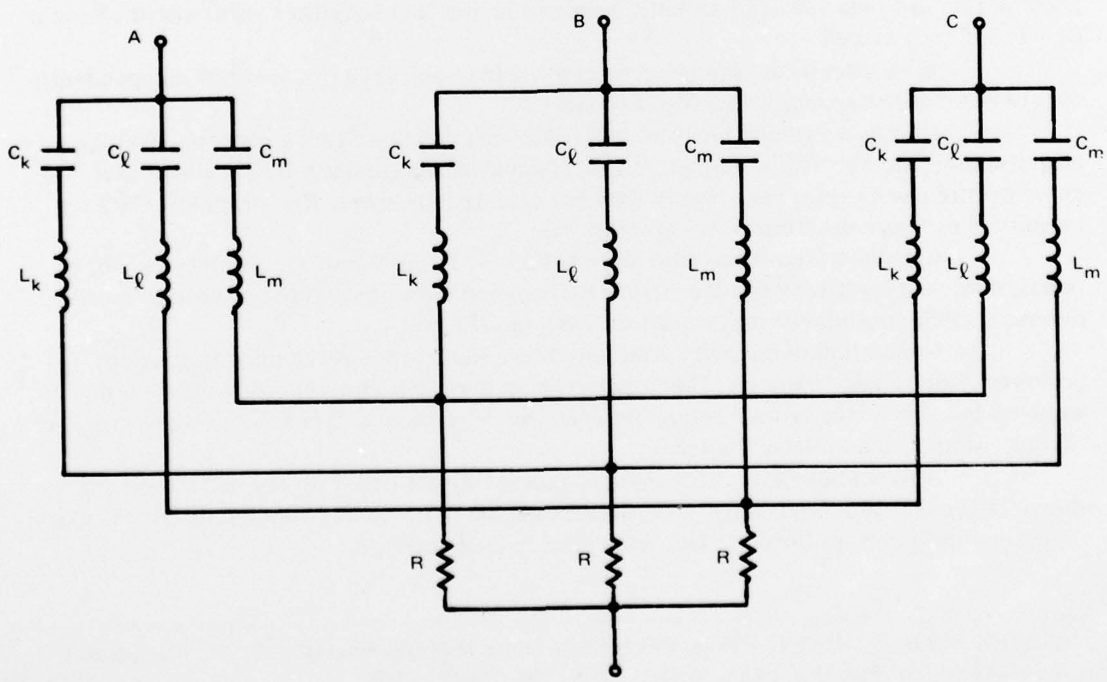

Figure D4. Three-phase interconnected filter.

1. In this IEEE article[D7] a method is described which the authors claim is not likely to be more expensive than elaborate filter equipment.

A third-harmonic current is injected into a duplex 6-phase rectifier by means of a third-harmonic current source paralleling an interphase transformer (fig D5). Although a duplex 6-phase rectifier is taken as an example, the authors claim the method is applicable to other types of converters. The interphase transformer has a high impedance; therefore the heavy third-harmonic current source will cause third-harmonic current to circulate around two secondary phases of the rectifier, and a corresponding balancing current will flow in the primary of the rectifier transformer.

This source must be capable of delivering a third-harmonic current comparable with half of the direct load current, and the phase of this current must differ by 90 degrees from that of the magnetizing current of the interphase transformer.

It is shown mathematically that all of the existing harmonics can be reduced (some to zero) depending on the injection ratio, ρ, which is the ratio of the triple-frequency injection current to the steady load current. A third harmonic is introduced, but the use of a delta primary can keep this harmonic out of the line current. Experimental results obtained were consistent with theoretical predictions.

For a rectifier, the source of triple-frequency current acts as a power sink. The authors mention that it is therefore possible to use a passive network such as a simple resistor to cause the required current to flow. Even so, this passive source must be capable of absorbing up to one-eighth of the dc load power. However, no further elaboration on the use of a passive network was presented.

2. Another paper[D8] describes a general theory for reducing harmonics in an ac line by modifying the current on the dc windings of the converter transformer through the injection of harmonic currents at a particular frequency. It is more general than the previous paper in that not only the 3rd harmonic is able to be injected but other 3nth-order harmonics ($n = 1, 3, 5 \ldots$) as well.

Basic circuits are shown to be applicable to any type of converter independently of types of rectifier arrangements (delta or star).

Calculated results for third harmonic injection ($k = 3$) are shown for varying magnitudes of the injected harmonic. Practical applications are described in which the experimental results agree very closely with the calculations, where the optimum relative magnitude of injected harmonic (ρ) is about 0.5.

Calculated results are also given for $k = 5$, 7, and 9, but these values are not of practical interest since they cause generation of current harmonics of the same and lower orders. (Only harmonics of orders higher than k are reduced.)

Generation of current harmonics of the same order as the injecting current occurs only on the dc windings. These papers show that no such harmonics occur on the ac windings because of the mutual action between the three phases. Thus the ac waveform becomes similar to a sinusoidal wave.

It might appear that the injected current would flow into the dc load circuit. But since the dc reactance is large, its inductance behaves for ac like a high impedance, and there is no influence on the dc circuit from the injected current.

[D7] Bird, BM, Marsh, JF, McLellen, PR, Harmonic Reduction in Multiplex Convertors by Triple Frequency Current Injection, Proc IEE, v 116, no 10, p 1730-1734, October 1969

[D8] Ametani, A, Generalized Method of Harmonic Reduction in AC-DC Converters by Harmonic Injection, Proc IEE, v 119, no 7, p 857-864, July 1972

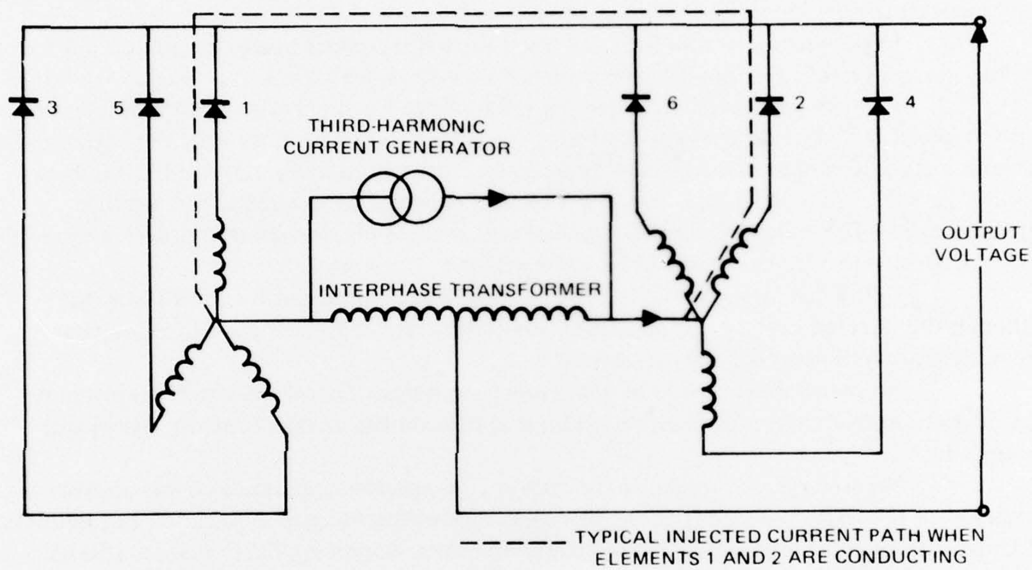

Figure D5. Current injection in duplex rectifier.

The authors feel that some of the problems remaining are the transient performance and the economics of this method relative to filtering.

3. This paper[D9] applies the principles and methods described in the author's previous paper[D8] to thyristor converters. Therefore, a firing delay angle, α, is theorized as another variable (see figure D2). Also, since commutation overlap is not considered to be instantaneous (as it was in ref D8) overlap angle, μ, is also a variable.

Some of the calculated results are shown. Harmonic reduction is shown to be dependent on μ and β, where β is the phase of the injected current, i_r, relative to the current waveform on the dc windings.

Experimental results were obtained for a three-phase bridge converter and for a double-star converter. For the bridge circuit with $\alpha \approx 5°$, $\mu \approx 5°$, $k = 3$ and $\beta = 0$, ac 5th, 7th, 11th, 13th, and 17th harmonic currents measured below 3 percent with optimum injection ratio of about 0.7. The double-star converter circuit proved to be more efficient. All ac harmonic currents were reduced to less than 2 percent with injection ratio of 0.22 (when $\alpha \approx 30°$, $\mu \approx 5°$, $k = 3$ and $\beta = 0$). Smaller injection currents are needed with a smaller injection ratio. The source of injected current was a single-phase stabilized power source of 330 VA consisting of a power amplifier and oscillator.

In the discussion following the paper it was pointed out by the author that although the injected currents will affect commutation and therefore overlap angle, his theoretical analysis assumed no such effect.

No mention was made of abnormal harmonics. Therefore, either no attempt was made to measure them or else they did not appear on the ac line with any significant magnitude.

No attempt was made by the author to assess the economics of this approach. However, in the written account of the discussion following the paper, Sachdev and Bennett, of University of Saskatchewan, Canada, suggested that a system application for a 150-kV, 1800 A bridge, for example, would require 2520 A rms third harmonic (1260 A per winding) for injected current, if $\rho = 0.7$. And for the capacitances needed in the experimental model, a series-parallel combination of capacitor units would have to be used to satisfy the voltage and current ratings simultaneously – possibly 18 capacitors in series and 80 capacitors in parallel for each of the two capacitances).

HARMONIC REDUCTION BY MULTILEGGED REACTORS (OR TRANSFORMERS)

1. A method is explained[D10] which uses a third winding in a transformer. A filter removes the fundamental component in a detected transformer secondary current. After filtering, the detected signal is amplified. This amplified current, devoid of the fundamental, is made to flow into the tertiary winding, thereby canceling the harmonic components in the magnetic flux.

This method will theoretically eliminate all harmonics, abnormal and normal.

Although no experimental work was attempted, considerable thought was applied to the design of a practical system. It was concluded by the authors that the system may be either impossible or not economical to design. Therefore, it is suggested that systems

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[D9] Ametani, A, Harmonic Reduction in Thyristor Converters by Harmonic Current Injection, IEEE Transactions on Power Apparatus and Systems, v PAS-95, no 2, p 441-449, March/April 1976

[D10] Sasaki, H and Machida, T, A New Method to Eliminate AC Harmonics Currents by Magnetic Flux Compensation – Considerations on Basic Design, IEEE Transactions on Power Apparatus and Systems, v PAS-90, no 5, p 2009-2019, September/October 1971

designers either undercompensate 5th and 7th harmonics, combining them with a conventional filter, or use 12-phase operation.

In the writeup of the discussion following the paper, Melvoid, of the Los Angeles Department of Water and Power, made the following interesting comments. A method such as this one, which attempts to eliminate the problem at its source, has much more merit than mere economic savings. There is an advantage gained by merely avoiding the pitfall of shunt-connected filters. When ac filters are connected to the ac bus, the low impedance causes an enormous concentration or converging to this one spot of ambient harmonic currents circulating throughout the power system (drawn by other loads and generators). He cited an example of an increase in the fifth harmonic from 2.9 to 15.4 amperes after energizing one ac filter bank.

2. An IEEE paper[D11] describes a method which uses multilegged reactors. A basic phase transformer winding for three phases wound on k cores is shown to ignore all harmonics in the limb fluxes except those for 1, 2k + 1, 4k + 1, etc. A 5-legged reactor thus ignores 3rd, 5th and 7th harmonics. These harmonic elimination properties are shown not to be greatly dependent upon magnetic imbalance in the cores. The reactor acts as a short-circuit trap for triplen harmonics generated externally.

This technique was developed during a study of phase transformation principles relative to the design of low-harmonic inductive reactors. Inductive reactors are used on power systems for compensating for system capacitance which might cause excessive voltage rises at light loads. It is usual to design them with a major air gap to limit iron saturation and minimize harmonics and noise. With such air gaps, the iron is used at uneconomically low flux densities. Also many-legged cores have recently been introduced elsewhere for a similar purpose but using different techniques, either transductor feedback circuits or harmonic traps.

The technique here shows how the windings may be employed in the design of three-phase iron cored reactors to make them relatively free from low-ordered harmonics. In particular, a winding technique called A_{11} was considered analytically and then experimentally for three phases on five single cores.

Experimental results were compared to the usual wye-connected winding (here designated Q) which has equal turns per phase on each leg. Some of the results of interest and possible applicability to transformers follow:

> Internally generated harmonics are mostly eliminated as seen from the waveform when A_{11} windings are used rather than Q windings.
>
> With externally generated harmonics supplying an A_{11} winding, the 5th, 7th, 11th, 13th, etc will cause currents of the same harmonic order to flow. But they will be relatively small, restricted by harmonic magnetizing impedances.
>
> With respect to externally generated zero-sequence harmonics, the new reactor has no internal impedance; it therefore acts as a perfect short circuit or harmonic trap to them.
>
> The material costs are likely to be significantly less than those for an equivalent plan [Q] gapped reactor. Construction costs may be greater.
>
> All experiments were made with separate cores. The asymmetry introduced by a single core of k legs is likely to be small. The building of a five-legged reactor is justified.

[D11] Parton, JE, Naman, QA, Harmonic-Free, Iron-Cored, 3-Phase Reactor, IEEE PES Summer Meeting, San Francisco, CA, July 20-25, 1975 (also discussions and closures on abstracted papers from the summer meeting)

Many of the results obtained here are applicable to a two-winding transformer having an A_{11} winding for primary or secondary.

In the discussion following the paper one of the participants commented that a six-cored reactor, described in the literature as a "twin tripler," is analogous to a 12-pulse bridge rectifier as far as its harmonic compensation features are concerned; hence a nine-core reactor, "treble tripler," is equivalent to an 18-pulse bridge rectifier. (He was objecting to the author's statement in the paper that a nine-cored reactor was not justified and only five cores result in an improved configuration.) The author's response to this criticism was that whatever the number of cores chosen (5, 7, 9, etc), the A_{11} winding (or an alternative, the B_{11} winding) will be superior.

HARMONIC REDUCTION BY CONTROLLED RECTIFICATION

The amplitude of specific powerline harmonics will vary with the firing delay angles and overlap angles of controlled rectifiers in converters. In several references, this concept was used to reduce harmonics. Three follow.

1. Reference D12 analyzes three types of static power supply (SPS) loads, but only the ac-to-dc rectifier analysis will be reviewed here. Figure D1 depicts a schematic power circuit for a typical familiar example of this device. Primary attention is directed toward fully controlled three-phase powered devices. For example, the rectifiers are silicon controlled rectifiers (SCRs), diodes with a controlled saturable reactor in series with each diode, or other similar devices.

This analysis assumes first that the load impedance on the output of the rectifiers is such that constant current results. (References are cited that such an assumption will, in general, be conservative and result in predictions of from zero to 20 percent higher than measured values.) Second, that no phase unbalance exists.

Prior to calculating harmonics, pertinent SPS parameters are identified as follows:

First, determine anode firing delay angle (α) and angle of overlap (μ) for the output load conditions being evaluated (see figure D2).

Second, identify the type of transformer-rectifier being analyzed (including no-transformer types).

Third, determine the fundamental power factor and total power factor under the output load conditions being evaluated.

Several methods are discussed to determine α and μ. One method consists of solving for α and μ from the dc voltage and current and commutating reactance (X_C). Xc consists of the combined commutating reactance of the transformer (ie, the leakage reactances) for the particular configuration used, the equivalent reactance of the supply system referred to the secondary side of the transformer, and any additional reactance in the anode (of the SCR) leads.

Procedures and tables are given to calculate the harmonics for different values of ripple factor, r, which is a function of the rectifier configuration. The report contains tables up to the 31st harmonic.

[D12]MPR-250, Handbook for the Calculation of Current and Voltage Harmonics on Three-Phase Shipboard Power Distribution Systems Due to Controlled Static Power Supplies, by MPR Associates, Inc for NAVSEC, August 1970, revised November 1970

The report also discusses methods of determining the harmonic voltages that appear in the power system due to an SPS load. The authors show how to calculate the impedances of some system loads, the generator impedance, and the cable impedances. The harmonic currents flowing through these impedances set up the harmonic voltages.

Finally, the last chapter discusses factors which influence initial design of static power supplies for minimum harmonic distortion. As a first approach the authors suggest line filters. However, they claim that past attempts in implementing line filters to reduce or trap the harmonics have achieved a reduction of only 45 percent of the fifth harmonics, 85 percent of the eleventh harmonics, and correspondingly greater reductions in the higher harmonics. The second recommended approach is to minimize distortion by proper design of the ac-to-dc rectifier.

The first step in such design is to determine the effective number of secondary phases and hence the value of the ripple factor, r. Increasing r reduces the harmonics. The authors of this paper state, however, that practical restrictions must also be considered when selecting r. They state that past experience indicates the existence of an instability problem under light load conditions in many 12-phase and in most greater-than-12-phase transformers. Due to the multiplicity and asymmetry of the windings, stable configurations generally have very low utility factors and correspondingly high kVA ratings, thereby representing larger and more costly systems. The authors also recommend system harmonic cancellations by the phase shifting of two r = 6 transformer type rectifiers. (If the primary of one is wye connected and the other is delta connected, harmonic distortions result as they would in an r = 12 rectifier for approximately equal loads.) Even if no deliberate system phase cancellation is attempted, partial cancellation will in fact occur if several loads are paralleled, as the result of reactances in cables and other loads between the points of load connection. Therefore, if several loads require a static power supply source, a single SPS rated at the total load would represent the worst case for harmonic distortion. Individual supplies should be implemented instead.

The second step in proper design of the ac-to-dc rectifier is to select transformer-rectifier parameters for minimizing harmonic distortion. With the use of equations and tables in this reference (D12), a selection is made of transformer configurations, turns ratio, and reactance. With these complex procedures, tradeoffs, and iterations, values of μ and α are obtained which result in minimum harmonic distortion. However, there seem to be practical limits on maximum values for μ. (For example, at $\alpha = 0$, μ max is smaller than 41 percent for the typical full-wave rectification. The tables show that the maximum theoretical reduction of the 5th harmonic current would be from 20 to 14 percent at $\alpha = 0°$.) Much greater reductions seem to result from the analysis described in the next paper.

2. A more recent study[D13] by personnel from General Electric analyzes methods of power factor improvement in their calculations. This is merely another way of achieving harmonic reduction, since in many power systems the poor power factor stems from harmonic input currents.

This analysis technique varies the delay angle (α) and turn-off angle (γ) for $\mu = 0$ (see figure D2) for the typical single-phase input currents obtained when solid-state power devices are fed. Graphic results are shown in which high (0.9) power factors are achieved for particular settings of α and γ.

Not only is the truncated square wave (figure D2) considered, as in the preceding study, but also other typical waveforms such as the truncated sine, symmetric cosecant,

[D13] Kornrumf, WP and Walden, JP, Power Factor of Active Filtering Systems, IEEE Power Electronics Specialists Conference, June 8-11, 1976

triangular, and finally a truncated composite wave (which approximates the truncated square, sine, and cosecant wave). The high (0.9) power factor is achievable in all of these cases.

Equations are given to calculate the power factors for the five current waves. Therefore, with proper control circuitry it may not be necessary to use heavy and bulky filter components.

3. A study[D14] on the reduction of harmonics (and filter weight) in aircraft-type cycloconverters assesses theoretically a negative feedback method to eliminate harmonics. Thyristor delay angles are again the variables that determine the harmonic amplitudes.

This 1970 study states that practical evaluation must await the development of suitable switches for firing circuits. Such switches may be available now, and negative feedback control may be a promising technique for harmonic suppression in converters.

HARMONIC REDUCTION BY A FREQUENCY TRANSFORMATION

Several references have proposed methods of increasing the frequency level of the harmonics and thereby reducing the filtering effort. Two of these references follow.

1. A PhD thesis by FC Schwartz[D15] presents a voltage wave-shaping process in which an aperiodic sampling technique forms a train of pulses varying in time and area. The pulse train is fed into a passive filter network. The desired wave shape, without harmonics, is obtained provided that sampling occurs with at least twice the frequency of its highest harmonic component and that the filter network eliminates all higher frequency harmonics generated by sampling. The latter fact follows from Shannon's sampling theorem.

The author states that the entire procedure is essentially lossless and affords considerable savings in size, weight, and energy losses. The experimental procedure was directed toward removing the ripple from the dc output of a power supply. However, the concept should have application in the reduction of harmonics from the powerline.

2. A technique discussed for inverters[D16] may have application for converters. Conduction of a silicon controlled rectifier (SCR) can be started and stopped by means of a control circuit. This ability makes it possible to have several conduction intervals during a single half-cycle of the fundamental frequency. If the conducting intervals of the SCRs are gradually increased and then decreased sinusoidally for an inverter, the load voltage varies sinusoidally. The lowest harmonic present in the output of the inverter is the repetition rate of the pulsing used. Thus the size and weight of the filter components are reduced at the cost of increased complexity in the control circuits. There is a reduction in efficiency since the losses due to commutation are proportional to the number of commutations per second.

Similar analysis and experimental work for converters in power supplies might result in a promising method for reducing powerline harmonics.

[D14] Royal Aircraft Establishment Technical Report 70250, Analysis and Reduction of Harmonics and Filter Weight in Aircraft-Type Cycloconverters, by GW Wilcock, December 1970, (AD 731463)

[D15] Schwartz, FC, A Class of Nonlinear Active Filters with Application to Electrical Energy Conversion, PhD Thesis, Cornell University, Ithaca NY, 1965

[D16] Bedford, BD and Hoft, RG, Principles of Inverter Circuits, p 312-313, John Wiley & Sons, 1964

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D13. Kornrumf, WP and Walden, JP, Power Factor of Active Filtering Systems, IEEE Power Electronics Specialists Conference June 8-11, 1976.

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